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CONDENSATION OF REFRIGERANTS ON
SMALL TUBE BUNDLES

by

Burlin Davis Mabrey

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Condensation of Refrigerants on Small Tube Bundles

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ABSTRACT

The construction of an apparatus for the condensation performance testing of a horizontal bundle of four tubes with various refrigerants was completed. The apparatus was instrumented, and data reduction software was developed to provide bundle and single tube condensation data.

Two tube bundles were tested, smooth copper tubes and low integral-fin copper-nickel tubes, with two refrigerants, R-114 and R-113. An enhancement ratio of about 2.0 for the overall heat transfer coefficient was demonstrated for the finned tubes over the smooth tubes.

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NOMENCLATURE

A_{ef}	Effective outside area of the tube (m^2)
A_f	Actual area of a finned tube (m^2)
A_i	Tube inside area (m^2)
A_o	Tube outside area (m^2)
A_r	Surface area of tube at the base of the fin (m^2)
C_i	Inside correlation coefficient
C_o	Outside correlation coefficient
C_p	Specific heat of coolant (J/kg K)
D_{eq}	Equivalent diameter of finned tube (m)
D_i	Inside diameter of test tube (m)
D_o	Outside diameter of test tube (m)
D_r	Root diameter of finned tube (m)
g	Acceleration due to gravity (m/s^2)
L	Length of the condenser tube (m)
LMTD	Log mean temperature difference (K)
N	Number of the tube from top of bundle
Ph	Phase Change Number
Pr	Prandtl Number
Q	Heat-transfer rate (W)
Q"	Heat-flux (W/m^2)
Re	Reynolds Number
Rm	Tube wall thermal resistance ($m^2 \cdot K/W$)
Res	Swirl Reynolds Number

Tc_i	Coolant inlet temperature (K)
Tc_o	Coolant exit temperature (K)
T_{sat}	Vapor saturation temperature (K)
U_o	Overall heat-transfer coefficient ($W/m^2 \cdot K$)

Greek

α_i	Inside heat-transfer coefficient ($W/m^2 \cdot K$)
α_i	Average inside heat-transfer coefficient ($W/m^2 \cdot K$)
α_o	Outside heat-transfer coefficient ($W/m^2 \cdot K$)
α_o	Average outside heat-transfer coefficient ($W/m^2 \cdot K$)
Δh_v	Specific enthalpy of vaporization (J/kg)
ΔT	Temperature rise of coolant across condensing length (K)
λ	Thermal conductivity ($W/m \cdot K$)
Γ	Mass flow rate of coolant (kg/s)
ρ	Density (kg/m^3)
η_{eff-f}	Fin efficiency
η	Dynamic viscosity ($N \cdot s/m$)

I. INTRODUCTION

A. BACKGROUND

With the advent of more complex shipboard weapons/combat systems and increasing fuel costs, the United States Navy has increasingly recognized a need for an energy-efficient, lightweight, and high-capacity air-conditioning system. Such an advanced system has been proposed and is currently in its test and evaluation phase for the DDG-51 program [Ref. 1].

Among the substantial differences in the advanced air-conditioning plant over extant systems is the use of titanium finned tubes in the condenser, in place of the smooth copper-nickel alloyed tubes previously used. The use of titanium in the air-conditioner's condenser presents two significant advantages. First, since the United States Navy uses ambient seawater as a heat sink, the corrosion resistance of titanium should measurably improve system integrity and reliability. Secondly, the advanced air-conditioning system expects to realize a weight savings per unit of 2286 kg (5040 lbs) and the major portion of this weight savings will come from the use of the lighter-weight titanium condenser tubes [Ref. 1].

Since the early 1970's the United States Navy has used R-114 as its primary refrigerant. The advantages of R-114 over the more-widely-used commercial refrigerants in a naval application derive from its low toxicity, temperature stability, stability when in contact with moisture, and its applicability to lower-pressure systems [Ref. 1]. R-114[1] will be the refrigerant utilized in the advanced air-conditioning plant.

As no substantial data base on the heat-transfer capacity exists for a system utilizing titanium condenser tube bundles configured as proposed in the advanced air conditioning plant and consequently, no way exists to measure this design's performance against competing designs, the need arose to develop a test apparatus to provide this data base in order to accurately predict future system performance. The design and subsequent construction of this test apparatus at the Naval Postgraduate School began in 1987 and is documented in the Theses of LCDR David S. Zebrowski [Ref. 2] and of LCDR Thomas J. Murphy [Ref. 3]. The test apparatus was also intended to serve as a test platform for advanced boiling surfaces proposed for use in the advanced air-conditioning plant. The incorporation of the advanced boiling surface test platform and a condenser tube test platform into a single test apparatus allows the widest latitude in examining the effects of various heat inputs, coolant flow rates, and various levels of refrigerant contaminants on individual components and overall system performance. Zebrowski and Murphy constructed

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[1]New refrigerants may have to be used in the future due to the "ozone problem."

the basic apparatus, and Murphy operated the system for preliminary evaporator measurements.

B. OBJECTIVES

The major objectives of this thesis were:

1. Refine the design and complete the fabrication of the apparatus for the testing of condenser tube bundles utilizing R-114 as the working fluid.

2. Develop and instrument a data-acquisition system with the associated software to provide a data base on the heat-transfer capacity of the condenser section of the test apparatus.

3. Validate the test apparatus by comparing condenser performance against extant data bases derived from conventional condenser tube bundles.

II. LITERATURE SURVEY

A. GENERAL OBSERVATIONS

Condensation is the phase transformation process in which a vapor is transformed to liquid by removal of latent heat. The promotion of condensation in heat exchangers is used extensively in applications for propulsion engineering and air-conditioning/refrigeration cycles. Due to its importance in the aforementioned fields, considerable research has been directed at the factors influencing the process and ways in which the process can be enhanced. Such factors as various modes of condensation, surface orientation to vapor flow, the shear forces exerted on condensate film, various external and internal surface enhancements, turbulent effects due to cascading condensate flow from another surface, and the effects of fluid properties on the process are detailed extensively in various reviews. This thesis deals exclusively with film condensation of refrigerants on small horizontal tube bundles in a quiescent vapor where tubes with external fins are compared to smooth tubes.

B. SINGLE TUBE INVESTIGATIONS

1. Smooth Horizontal Tube Studies

The first comprehensive condensation model was developed by Nusselt in 1916 [Ref. 4] based on the assumption that a quiescent vapor at saturation temperature coming into contact with a wall surface below saturation temperature would condense and form a continuous film of condensate growing in thickness as the film flowed off the surface under the influence of gravity. The condensate film at the vapor-liquid interface would be at the vapor saturation temperature with a temperature gradient in the film down to the wall surface temperature. No radiation or convection would take place at the liquid-vapor interface as both liquid and vapor are at the same temperature, however the amount of vapor condensing corresponds to the quantity of heat flowing through the film by thermal conduction. In the case of a horizontal tube, he assumed that condensate flows in a laminar manner around the sides of the tube and off the tube in a continuous sheet. The heat transfer coefficient would be maximum at the top center of the tube decreasing gradually around the surface of the tube, as the inherent thermal resistance in the film grows with the thickness of the film, and eventually goes to zero at tube bottom. Nusselt's model is limited by disregarding surface tension forces that tend to hold up condensate at the tube bottom until overcome by gravity, resulting in the production of condensate droplets rather than a continuous sheet. Nusselt's expression for the average heat transfer coefficient for a single tube subjected to a constant heat flux is given by:

$$\bar{\alpha}_o = .655[\lambda_f^3 \cdot \rho_f^2 \cdot g \cdot \Delta h_v / \eta_f \cdot D_o \cdot Q'']^{1/3} \qquad (2.1)$$

Although constrained by the aforementioned limitations, Nusselt's model remains the conservative bench-mark against which all other models are compared.

2. Exterior Surface Enhanced Tubes

Research into ways to improve condensation performance in condensers is motivated by the idea that any force that acts to thin the condensate film promotes an enhancement of heat transfer by minimizing the resistance to heat flow. General enhancement techniques include the fabrication of surfaces that promote dropwise condensation, wrapping exterior surfaces with wire, installation of porous drainage strips, and the fabrication of finned tubes with fins of various geometries and various spacings along the tube. This thesis deals with a low integral-fin tube and its heat transfer enhancement over a smooth tube.

In considering a low integral-fin tube during condensation, there exists two distinguishable regions on the circumference of the tube; a flooded region and an un-flooded region. The flooded portion of the tube defines the condensate retention angle of the tube with respect to the tube circumference. The smaller the condensate retention angle of the tube, the larger the heat transfer capacity of the tube. The fin can be divided into three regions; the fin tips, the sides of the fins, and the fin root area. The majority of heat transfer takes place at the fin tips. Surface tension forces pull the condensate from the tips down the fin sides into the flooded root area, where gravity drains the condensate to the bottom of the tube. The amount of condensate retained along the circumference of the tube is dependent upon the ratio of surface tension forces to gravity forces.

Beatty and Katz [Ref. 5], in 1948, developed a comprehensive model for the prediction of the heat transfer coefficient of finned tubes based on their experimental results for various test fluids (including R-22) and finned tubes of various metallic compositions, and various fin geometries. Their model assumes gravity-dominated flow and neglects surface tension effects completely. Subsequent experimental results from other sources indicate that the Beatty and Katz model overpredicts the heat transfer coefficient as surface tension increases or as fin density increases. Nevertheless, the Beatty and Katz model conformed to their reported overall heat transfer enhancement of up to 2.3 for R-22 on finned tubes compared to smooth tube data. The Beatty and Katz model is given by:

$$\bar{\alpha}_o = .689 \cdot [\lambda_f^3 \cdot \rho_f^2 \cdot g \cdot \Delta h_v / \eta_f \cdot \Delta T_{vf}]^{1/4} \cdot [\frac{1}{D_{eq}}]^{1/4} \tag{2.2}$$

where,

$$[\frac{1}{D_{eq}}]^{1/4} = \frac{A_r}{A_{ef}} \cdot \frac{1}{D_r^{1/4}} + 1.30 \cdot [\eta_{eff-f}] [\frac{A_f}{A_{ef}}] [\frac{1}{\bar{L}^{1/4}}] \tag{2.3}$$

and,

$$\bar{L} = \pi \cdot (D_o^2 - D_r^2)/4 \cdot D_o$$

A three-region theoretical model, based on their experimental results with three rectangular finned tubes, was presented by Karkhu and Borovkov [Ref. 6], in 1971, including surface tension forces. Measured heat-transfer coefficients demonstrated a 50 to 100 percent increase in vapor-side heat transfer coefficients for steam and R-113 condensing on finned tubes compared to smooth tubes. Unfortunately, they did not report enhancements separately for the two fluids. In 1980, results reported by Carnavos [Ref. 7] condensing refrigerants on various finned tubes demonstrated an enhancement of up to 400 percent in the heat transfer coefficient over smooth tube results. Work done by Sauer and Williams [Ref. 8], in 1982, on the condensing performance of finned tubes with oil-contaminated R-113 demonstrated a serious degradation of performance when the surface tension to density ratio was large. The conclusion formed was that the higher-surface-tension oil remained in the fin gaps rendering the finned surface ineffective. Results reported by Honda et al. [Ref. 9], in 1983, condensing R-113 on finned tubes of various geometries showed improvements of 900 percent for the vapor-side heat transfer coefficients at a constant vapor-to-tube-wall temperature difference. The results reported by Kabov

[Ref. 10] in 1984 with refrigerants R-12 and R-21, indicated that the bulk of the latent heat was in fact removed on the lateral fin surfaces and that an optimum fin height and spacing was dependent upon the ratio of surface tension to gravity forces. The results published by Masuda and Rose [Ref. 11] in 1985 in experiments with R-113 condensing on low integral-fin tubes, confirmed that the overall heat transfer coefficient increases, in general, with decreasing fin spacing. Their results showed a 600 percent increase in enhancement over smooth tube performance. More recent results by Marto et al. [Ref. 12] with R-113, demonstrated a 700 percent enhancement in performance over a smooth tube and gave an optimum fin spacing of 0.5 mm for that fluid. Work performed and published in the same time frame by Sukhatme et al. [Ref. 13] with R-11 on conventional integral-fin tubes and special pyramid-shaped fin tubes, reported enhancement ratios of 5 to 7 for the low integral fin tubes and 10.3 to 12.3 for the pyramid-shaped fin tubes.

C. TUBE BUNDLE INVESTIGATIONS

1. Smooth Tube Bundles

In smooth tube bundles, two conflicting factors play a role in determining bundle performance. First, the condensate flowing from the tubes above a given tube in a bundle tends to thicken the condensate film on that tube, hence increasing the resistance to heat transfer. This effect is known as the condensate inundation effect. Secondly, droplets from other tubes striking the film surface on a tube with a velocity provided by gravity or vapor flow, can create ripples or waves in the condensate film imparting a turbulence within the condensate film that produces an enhancement of heat transfer performance.

In 1949, Jakob [Ref. 14] elaborating on Nusselt's model, predicted that the vapor-side heat transfer coefficient for a tube in a bundle, compared to the first tube in the bundle, was a function of that tube's relative position in the bundle. This model was based upon the assumption that a continuous laminar sheet of condensate flowing off the tube directly above the tube considered and striking the top of this tube further thickened the condensate film on this tube. Jakob's model is given by:

$$\frac{\bar{\alpha}_N}{\alpha_1} = N^{-1/4} \tag{2.4}$$

In 1958, Kern [Ref. 15] proposed a model based on the assumption that discrete droplets or jets of fluid from other tubes caused ripples in the condensate film diminishing the inundation effect. Kern's model is less conservative than Nusselt's and, in many cases, remains the applied industrial design standard. Kern's model is given by:

$$\frac{\bar{\alpha}_N}{\alpha_1} = N^{-1/6} \tag{2.5}$$

Work by Chen [Ref. 16], published in 1961, proposed a model that considered the momentum gain of falling condensate as well as the condensation of vapor on sub-cooled condensate droplets or sheets. Chen's model which is essentially Nusselt's model times a factor that incorporates the phase change number is given by:

$$\frac{\bar{\alpha}_N}{\alpha_1} = N^{-1/4}[1 + 2 \cdot Ph \cdot (N-1)] \tag{2.6}$$

where the Phase Change number is given by:

$$Ph = \frac{C_p \Delta T}{\Delta h_v}$$

Equation (2.6) is valid provided,

$$Ph \cdot (N-1) \leq 2.0$$

A model proposed by Eissenberg [Ref. 17] in 1972, assumes that condensate does not always drain in a vertical direction but may be diverted sideways due to local vapor flow conditions. In this case, the condensate strikes subsequent tubes on their sides rather than on their tops, minimizing inundation effects on the condensate film in the top portion of the tube. Eissenberg's model is given by:

$$\frac{\bar{\alpha}_N}{\alpha_1} = .60 + .42 \cdot (N^{-1/4}) \tag{2.7}$$

2. Enhanced Tube Bundles

Katz and Geist [Ref. 18] in 1948, studying six fin tubes in a vertical row, using R-12 among other working fluids, found that the effect of condensate inundation was over-predicted by Jakob's model and proposed that the exponent in Equation (2.4) be changed to 0.06 for finned tubes.

A theoretical model was proposed by Honda et al. [Ref. 19] in work published in 1987, for finned tube bundles that showed good agreement, within 5 to 7%, for data taken condensing acetone and R-12 on finned tubes. Their model relies upon solving a set of algebraic equations describing the vapor-to-coolant conjugate heat transfer problem. A compendium of the aforementioned models, both single tube and bundles, is provided by Marto [Ref. 20].

As of the date of this writing, the author is unaware of any comprehensive model, substantiated by experimental results, that accurately predicts heat transfer performance for enhanced tube bundles with varying fin geometries and varying pitch.

III. EXPERIMENTAL APPARATUS

A. CONDENSER/BOILER TUBE BANK TEST PLATFORM

1. Overview

The composite test platform, with associated support systems, is depicted schematically in Figure 3.1. The boiler/ condenser unit was fabricated from 6.35 mm thick, rolled stainless steel plates designed to withstand an absolute pressure of 308 kPa. The top cylinder which serves as the condenser for the apparatus is 1.30 m in length with an external diameter of 0.61 m. The effective condensing length is 1.22 m. The condensing chamber is capped on either end with circular stainless steel plates of 0.71 m diameter and connected to the chamber with a flange and stud assembly. System integrity is maintained with a 3.20 mm thick rubber gasket. The end caps support the nylon block condenser tube mounts, stainless steel backing plates, auxiliary condenser coils (coolant entrance side), and mixing chambers (coolant exit side). The condenser chamber has five 12.7 mm thick Pyrex glass view ports backed with 12.7 mm thick Plexiglas. The view ports are 127 mm in diameter and are located axially along the main chamber, angled so as to provide top to bottom views of the test tubes at various locations along the effective condensing length. The condenser chamber and

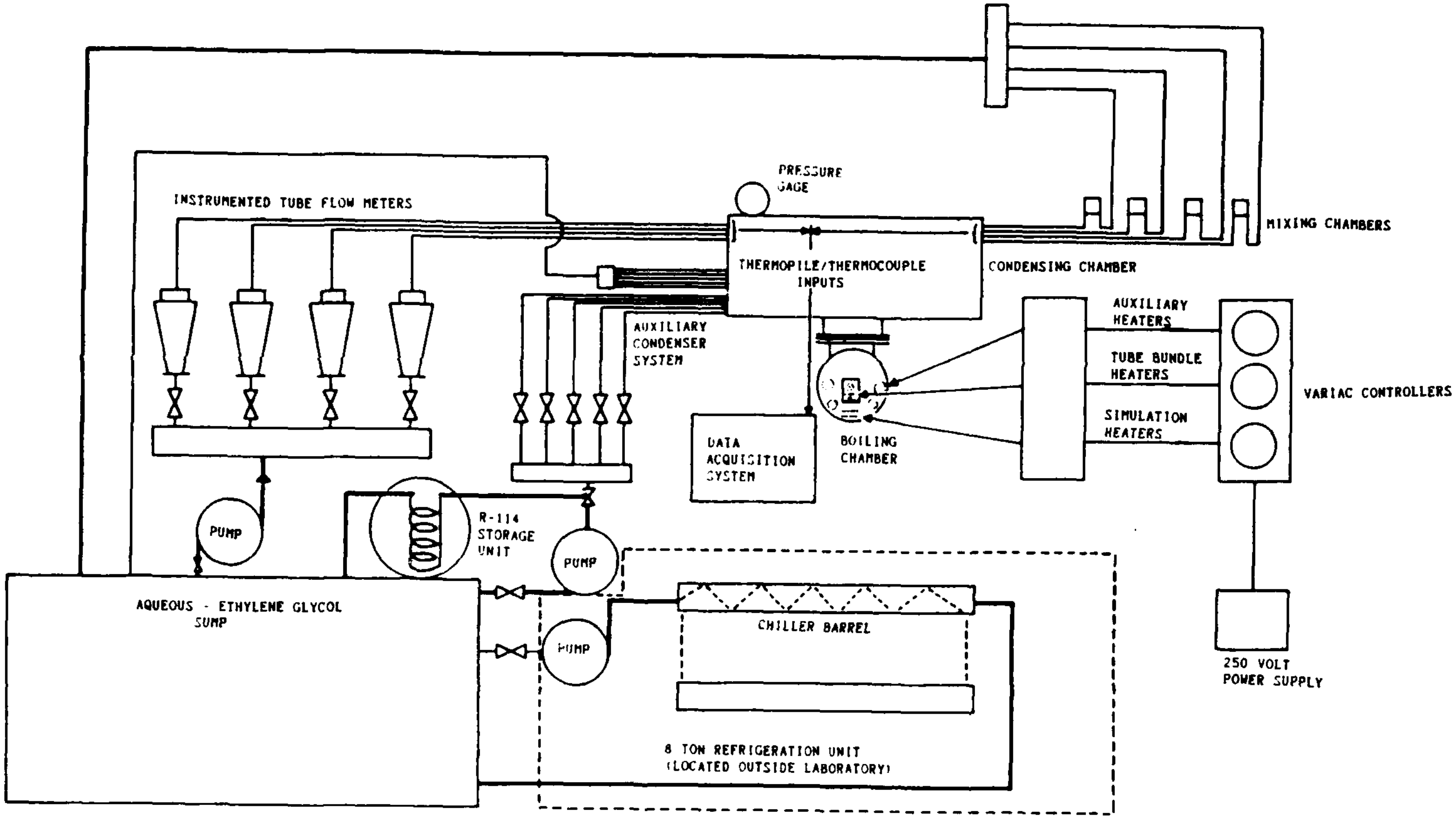

Figure 3.1 System Schematic

ancillary equipment are depicted graphically and in photographs in Figures 3.2 through 3.5.

Internal to the condenser chamber, a stainless steel shroud is fitted over the effective condensing length of the instrumented test tubes (see Figure 3.6). The purpose of the shroud is to channel refrigerant vapor along the inside circumference of the shell, collecting vapor at the top, and then forcing vapor through the vertical axis of the instrumented tube bank into the shroud's well, where condensate is collected and the remaining vapor is condensed by an auxiliary condenser. The auxiliary condenser is composed of five helically wound copper tubes of 9.53 mm diameter suspended inside the shroud well by cantilevered rods welded to the entrance end cap. The stainless steel shroud was fabricated with a glass panel serving as one side of its stem to permit viewing of the instrumented tubes through the view ports.

The condenser chamber is attached to the boiler chamber by a rolled stainless-steel cylinder nominally 280 mm in diameter and 203 mm in length, located mid-way along the condenser chamber's length allowing condensate to drain by gravity. A collar dam was fitted at the connecting flange, for the initial purpose of providing a condensate drain point to send condensate to the auxiliary storage unit. Subsequently, a faster, more-efficient method of transferring refrigerant was devised that allowed refrigerant vapor to be

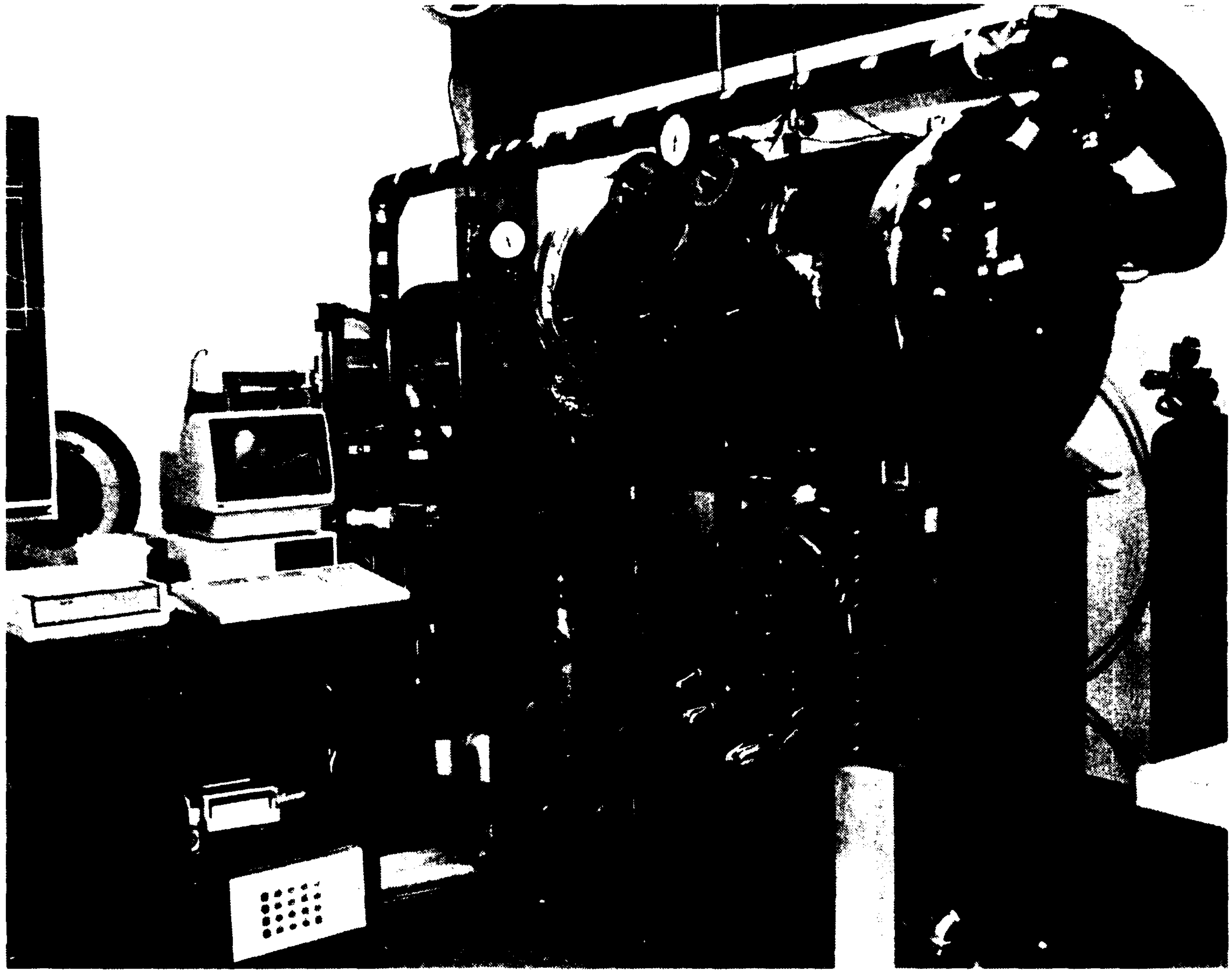

Figure 3.2 Photograph of Apparatus and Support Systems

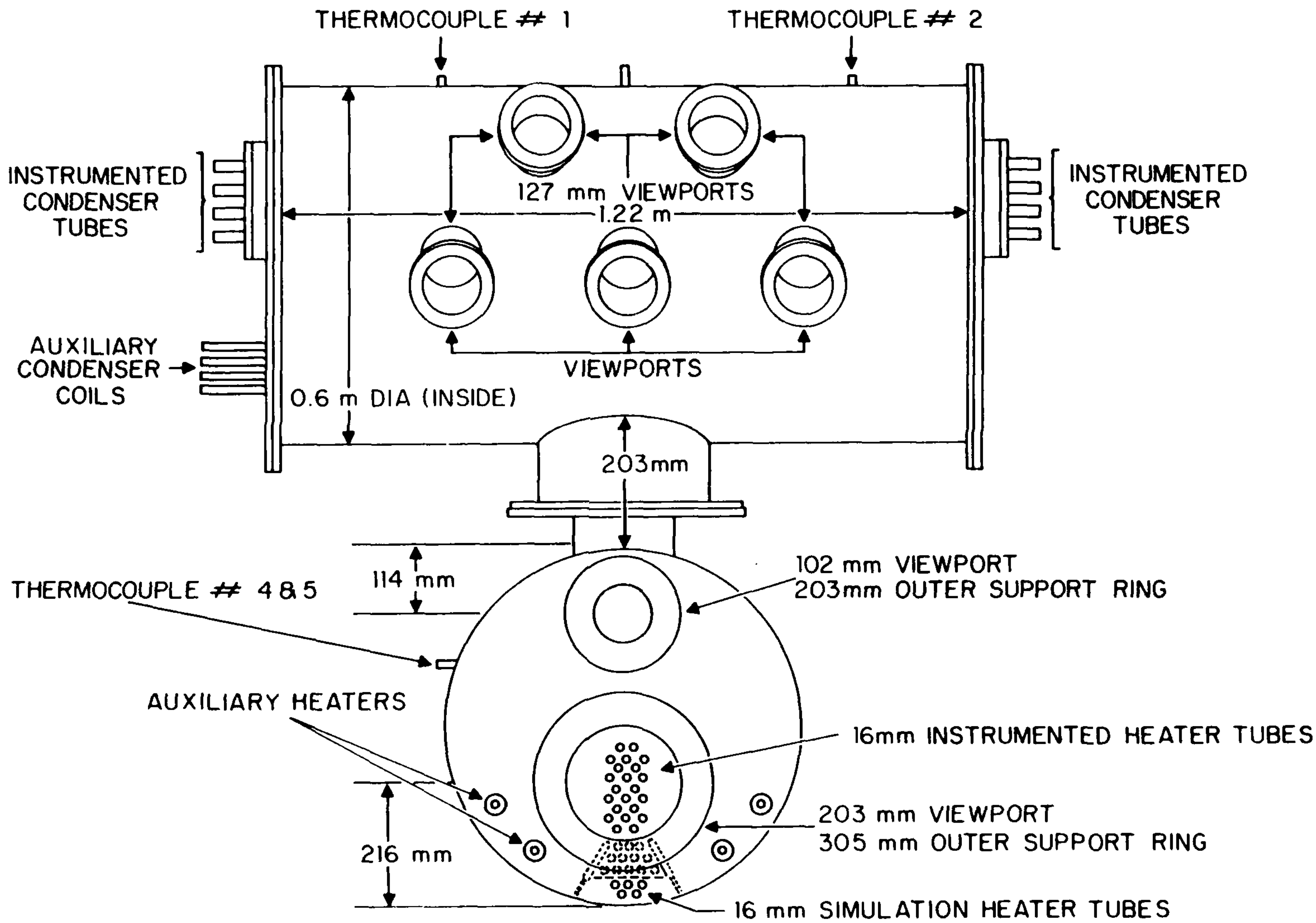

Figure 3.3 Apparatus Schematic

Figure 3.4 Photograph of Coolant Entrance Endcap

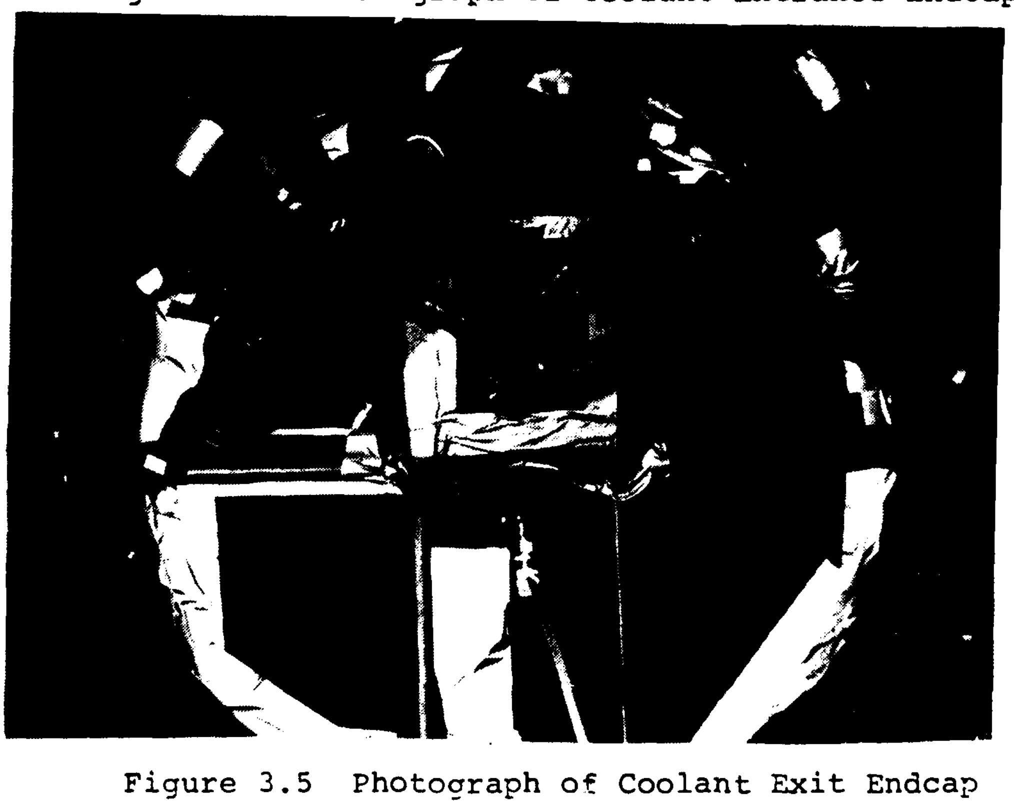

Figure 3.5 Photograph of Coolant Exit Endcap

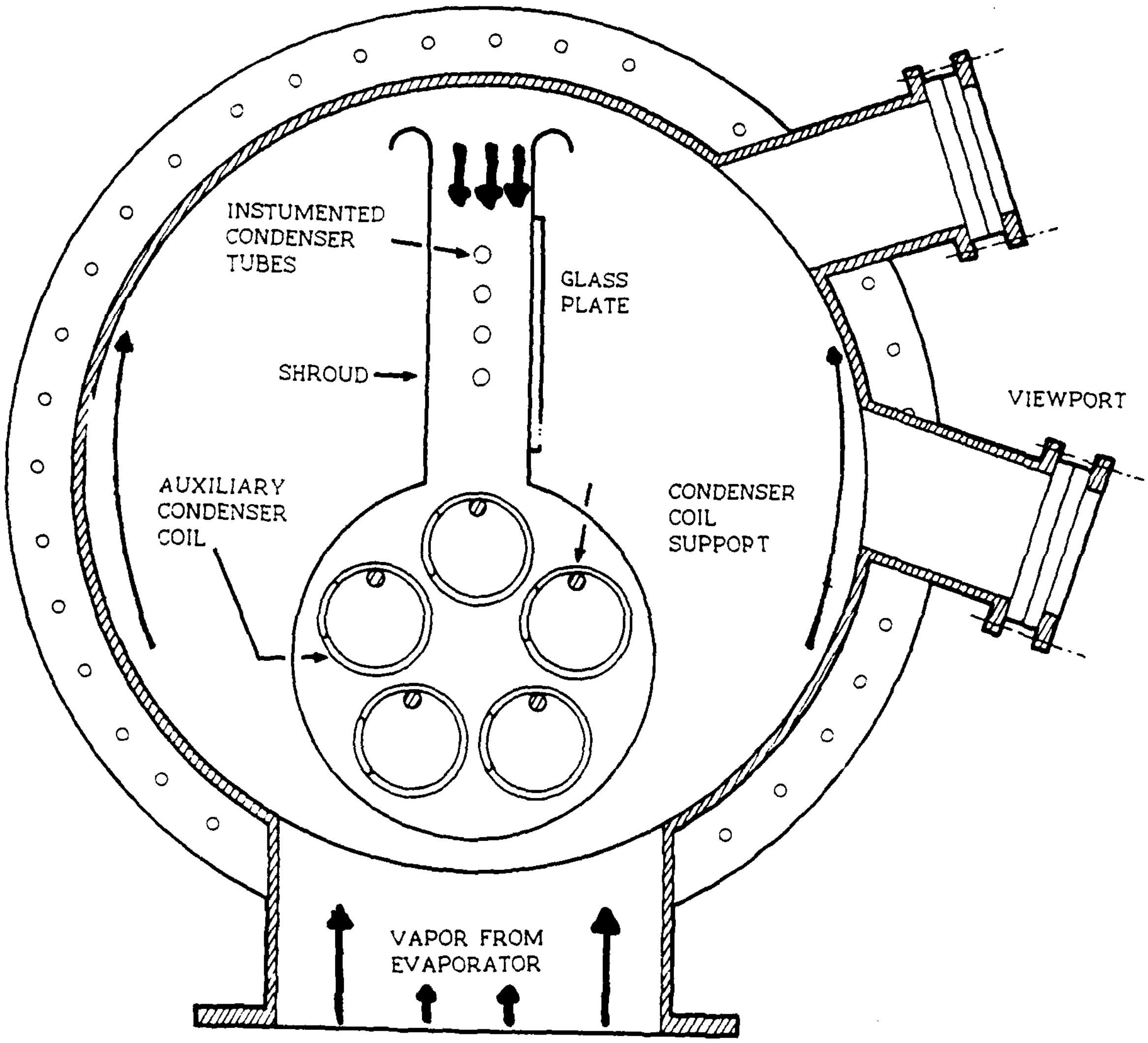

Figure 3.6 Cross-section of Condensing Chamber Schematic

sent and condensed in the auxiliary storage unit. A 9.53 mm diameter copper tubing was provided for the vapor flow from the top of the condenser chamber to the storage tank. A similar tubing was provided between the storage tank and the boiling chamber to allow liquid flow via gravity.

The boiling chamber is connected to the condenser unit via the interconnecting riser as previously discussed. The boiling chamber was also fabricated from rolled stainless-steel and is cylindrical with an outside diameter of 0.61 m and a length of 0.279 m. The boiling chamber is fitted with two Pyrex view ports, strengthened by Plexiglas plates, for observation during operation. The boiling unit is comprised of three groups of tubes (see Figure 3.3). In the simulation tube bundle, there are five boiling tubes each nominally rated at 1.5 kW and located at the bottom of the boiler unit. In the auxiliary tube bundle, there are four boiling tubes each nominally rated at 4 kW and located two on either side of the instrumented tube bundle. The instrumented tube bundle is located in the lower center of the boiling unit and is comprised of 35 tubes, with ten active tubes rated at one kW each, five instrumented tubes, and 20 dummy tubes. The power provided to these tubes is controlled by three variac controllers located on a console adjacent to the test platform and fed by a 208 volt power supply. The variac controllers are graduated in one percent increments of maximum power for each tube bundle. The exact location of each tube bundle is apparent in Figures 3.2 through 3.5. It is a unique feature of this test platform that both boiling and condensation phenomena in a closed loop system can be evaluated simultaneously. Details on the design and construction of the basic test platform are available from Zebrowski [Ref. 2] and Murphy [Ref. 3]. Lightoff and securing procedures for the apparatus are listed in Appendix B.

2. Ancillary Systems

Component equipment that support the R-114 tube bundle test platform and are located external to the apparatus include: (1) an R-114 storage and transfer system, (2) a condenser cooling and flow control system, (3) a coolant (62.4% by weight mixture of ethylene glycol and water) sump, and (4) an eight-ton refrigeration unit.

The R-114 storage and transfer system, as previously described, consists of a stainless-steel cylindrical tank 0.350 m in diameter and 0.91 m in length located on a rack above the coolant sump. Transfer of the refrigerant is accomplished by boiling in the main boiling chamber with vapor being sent to the storage tank via 9.53 mm diameter copper tubing located in the top center of the condenser chamber. The vapor is condensed in the storage cylinder by means of a helical copper coil, suspended the length of the cylinder on a cantilevered bar, that is kept cooled by the water-ethylene glycol mixture. Liquid refrigerant can be returned by gravity to the test platform from the bottom of the storage tank through a 9.53 mm diameter copper tubing to the boiling chamber. Faster transfer of R-114 liquid was also possible if the system pressure was at or below the atmospheric pressure. Notice that the storage tank experiences an absolute pressure of about 210 kPa.

Coolant and flow control to the test apparatus and ancillary equipment is accomplished by two different flow path systems. Both flow systems are driven by two 0.5 HP constant-speed pumps that take suction on the main coolant sump. The coolant for the test condenser tube bank passes from the pump discharge through 76 mm diameter PVC piping to a Plexiglas header. At the header, flow is split and proceeds through 15.9 mm diameter Tygon flexible tubing to a bank of rotameters. Flow can be controlled by throttling a gate valve located at the entrance to each flow meter. Coolant flow leaves the exit of each flow meter and proceeds to the instrumented condenser tube bank through flexible Tygon tubing. At the exit of the main condenser chamber, coolant leaves each tube and flows through flexible Tygon tubing to individual mixing chambers (Figure 3.7). From the mixing chambers, coolant passes through flexible Tygon tubing to a central Plexiglas header suspended above the test platform, and the collective coolant is piped back to the main sump through 76 mm diameter PVC pipe. Auxiliary coolant flow leaves the pump discharge through PVC piping and proceeds to a two-way ball valve, where the flow is either sent to the

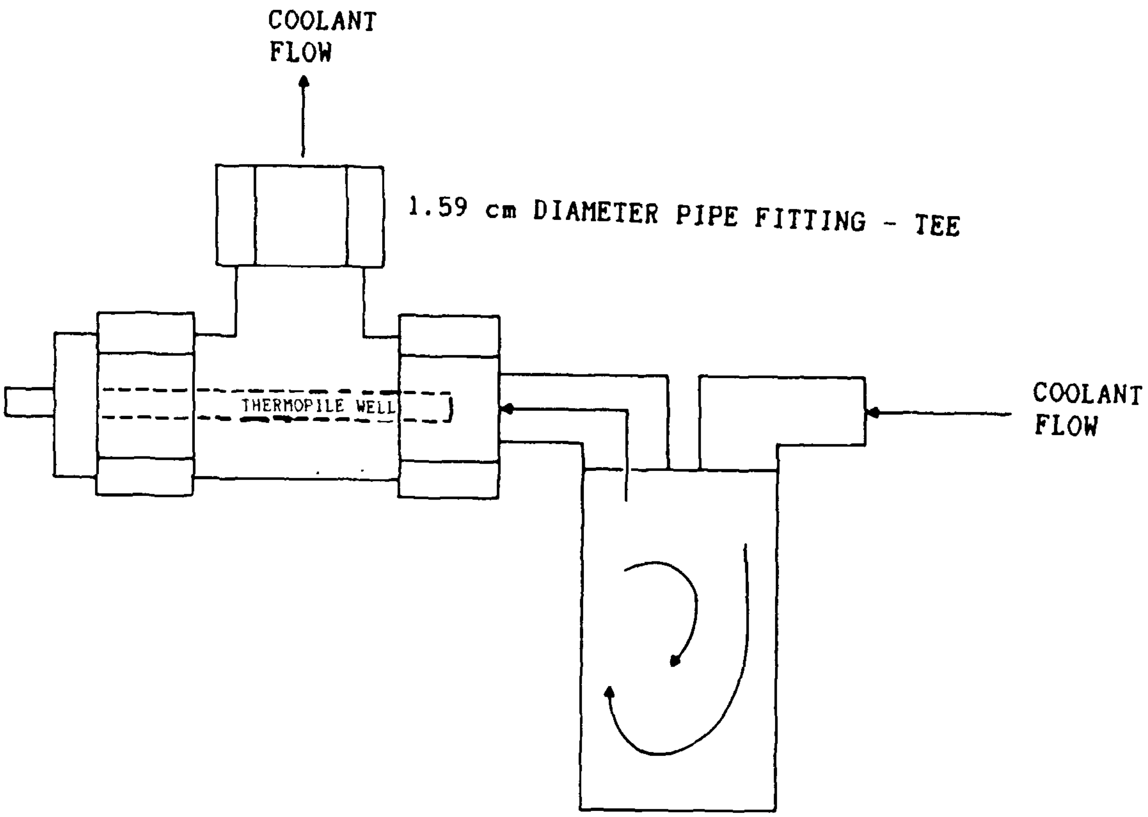

Figure 3.7 Mixing Chamber Schematic

R-114 storage tank and back to the main sump or is sent through PVC pipe to a large rotameter. From the auxiliary flowmeter, coolant enters a central header and is then split to flow to the five auxiliary condenser coils and back to the coolant sump. Flow through each auxiliary condenser coil is controlled by a valve located at the coil inlet. The coolant sump has a 1.81 cubic meter capacity and is constructed of 12.7 mm thick sheets of Plexiglas. The coolant is approximately 62.4% ethylene glycol and 37.6% water (by weight).

The coolant is chilled by an externally-located, 8 ton refrigeration system that continually re-circulates sump coolant with a 0.75 HP pump. The refrigeration system is capable of maintaining a sump temperature between -21 C and ambient temperature.

3. Instrumentation

The coolant temperature rise is measured by series-connected thermopiles having ten junctions on either end. These thermopiles were fabricated using type-T thermocouple wire. The ends of the thermopiles are inserted in stainless steel wells with copper-plugged tips located at the entrance to each individual condenser tube and at the exit of this tube's mixing chamber. Inlet coolant temperature is measured with type-T thermocouples also located in the entrance wells. Refrigerant liquid and vapor temperatures are measured with type-T thermocouples inserted in stainless-steel wells at the locations indicated in Figures 3.2 through 3.5.

System pressure is monitored through a calibrated pressure-vacuum gage valid over a range of 30 inches mercury (vacuum) to 30 pounds per square inch (gage pressure).

4. Tube Bundle Data Acquisition and Reduction

A Hewlett-Packard 9816A computer was used to control a Hewlett-Packard 3497A Automatic Data Acquisition System, which read the output of the thermopiles and thermocouples. Readings were made in millivolts and were converted to temperature readings in the data reduction program. The channels read by the data acquisition system are listed in Table 3.1.

5. Tubes Tested

Two sets of tubes were tested. The first was a smooth copper tube (inside diameter 13.26 mm, outside diameter 15.88 mm) and the second was a low integral-fin copper-nickel tube (inside diameter 10.16 mm, root diameter 14.00 mm, outside diameter 15.88). These two sets of tubes were tested, in bundles and individually, with R-114 and R-113.

TABLE 3.1

CHANNEL ASSIGNMENTS ON DATA ACQUISITION SYSTEM

Channel Numbers	Measurement
0-2	Vapor Saturation Temperature
3-4	Liquid Temperature
5	Inlet Temperature coolant 1st Tube
6	Inlet Temperature coolant 2nd Tube
7	Inlet Temperature coolant 3rd Tube
8	Inlet Temperature coolant 4th Tube
20	Thermopile 1st Tube
21	Thermopile 2nd Tube
22	Thermopile 3rd Tube
23	Thermopile 4th Tube

IV. SYSTEM OPERATION AND DATA REDUCTION

A. TEST PLAN AND MODIFICATION OF DESIGN FOR CONDENSER TEST APPARATUS

1. Ability to Change Working Fluids

Although envisioned in the original apparatus design by Zebrowski [Ref. 2] and Murphy [Ref. 3], no physical system existed for the change-out and storage of working fluids. The system was designed as a general test platform to evaluate the performance of various refrigerants and steam during condensation on a variety of test tubes.

The R-114 storage and transfer system as described in Chapter III, ancillary systems, was designed and built to allow for the storage of refrigerants that evaporate at atmospheric temperature and pressure. This additional capability not only conserves expensive refrigerants but facilitates speedy change of these working fluids during the evaluation of a particular tube with a variety of refrigerants.

2. Tube Alignment and Reduction of Tubes in Test Bundle

Visual inspection, during preliminary experimental runs, revealed that bowing of the tube bundle was detrimentally affecting condensation patterns. As a result of misalignment of the endcaps during fabrication, bending moments of varying magnitudes and directions resulted in condensate flow striking subsequent tubes in the vertically-oriented bundle at different positions around the circumference of the tubes. Upon disassembly of the end plates of the apparatus and comparison with the proposed drawings for the DDG-51 refrigeration condenser provided by the David Taylor Research Center, miscalculations in the tube pitch were revealed. The vertical pitch required for the project is 35.74 mm, centerline to centerline. The nylon bundle plates, as manufactured, had a pitch that was considerably less. In an effort to correct the tube mis-alignment problem, a low-powered laser was proposed to align the bundle tubes. A new nylon endplate was fabricated for the exit endcap, at the correct pitch with the tube bundle reduced to four vertical tubes,due to constraints in the endcap openings. An aluminum mount for the laser was fabricated by machine shop personnel that fit snugly into the tube penetrations of the nylon block. Several test projections were conducted on a plastic template fitted to the entrance endcap to minimize misalignment possibilities. The plastic template was scribed and cut with particular attention paid to correct pitch and used to manufacture the entrance nylon endplate. Subsequent visual inspection during experimental runs revealed that misalignments and bowing had been corrected.

3. Vapor Superheat Problems

During initial experimental runs, observed discrepancies in the measured temperature increases across the condenser tube lengths when compared to predicted temperature increases, prompted consideration of the possibility of vapor superheat occurring as vapor (at saturation temperature less than room temperature) flowed from the boiling chamber through the riser and up the sides of the condensing chamber. A two-pronged strategy was developed to minimize this possible effect. First, the apparatus shell was completely insulated with 12.7 mm thick foam insulation and all ancillary tygon tubing was insulated with double-wrapped, 3.18 mm thick foam insulation. Secondly, all experimental runs were performed at vapor saturation temperatures above the ambient temperature.

4. Contamination Problems

Visual inspection of the condensing tubes during operation, correlated with observed disparities in measured temperature increases across condenser tubes, revealed a structured, crystalline surface or matrix formation on the tube surfaces that inhibited heat transfer. The first appearance of the inhibiting matrix occurred during runs with smooth copper tubes and with the coolant inlet temperature at approximately -20 C. The working fluid, R-114, was transferred to the storage unit except for an oily residue that remained in the bottom of the boiling chamber. This residue was not analyzed, but was assumed to be machining oil that remained after apparatus fabrication. The system was flushed twice, once with acetone and once with R-113, and the boiling chamber was scrubbed out. The smooth copper tubes were re-installed after a complete cleaning of their outside surfaces, and the experimental runs were repeated under the same conditions. Visual inspection again revealed the presence of the matrix formation on the tubes, and the possibility of water contamination in the R-114 was conjectured as a probable cause. The matrix was thought to be ice crystals solidified on the tube surface. The decision was made to continue experimental runs with a different refrigerant (R-113) and a different type of condensing tube (copper-nickel 1024 fpm low integral-fin tube), with the aim of understanding the conditions that caused the phenomena to exist. First, a run was made using R-114 with the copper-nickel finned tube under exactly the same conditions as described in the smooth copper tube runs. Visual inspection, during this run, revealed an apparent thickening of the fins at the top of the tube when compared visually with the second tube (see Figure 4.1(a) fin normal appearance and Figure 4.1(b) fin's thickened appearance). This appearance of thickening gave credence to the belief that water contamination was causing an ice layer to form on the top tube between fins. The refrigerant was then changed to R-113 and the run was repeated, with the inlet cooling temperature at approximately -20 C. Again, a marked thickening of the finned

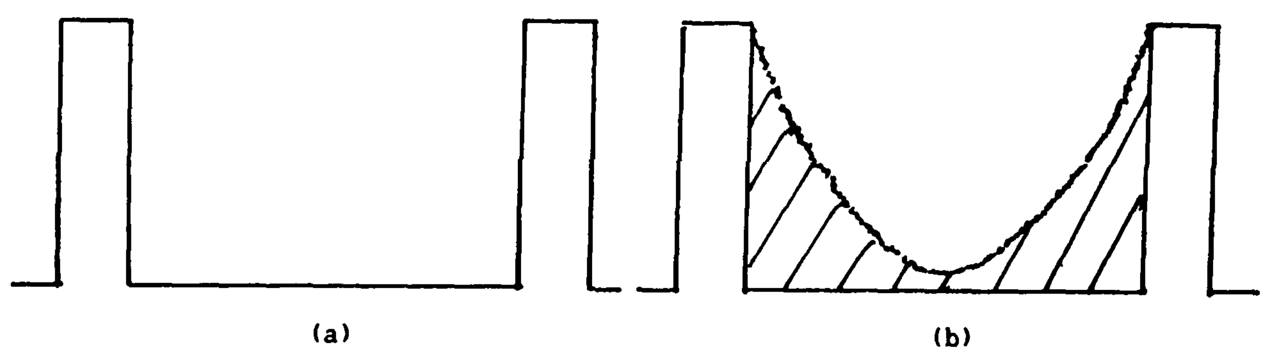

Figure 4.1 Cross-section of Fin Surface Schematic

surface appeared on the top of the first tube. The next experimental run was conducted on the same finned tube with R-113, but at a coolant inlet temperature slightly above 0 C. In this situation, no visible thickening of the finned surface was observed, but disparities in temperature increases across tube lengths persisted. The run was repeated several days later to observe whether the phenomenon consistently repeated itself. Finally, the smooth copper tube was substituted for the finned tube and the experimental run repeated at the higher coolant inlet temperature. Noticeable surface contamination, having an orange peel appearance, recurred. In addition, during this run, there were indications that a pocket of non-condensable gases formed in the top of the condensing chamber. As every effort had been made to evacuate the apparatus prior to commencing the experimental run, and no evidence exists to support outside leakage of air into the system, the possibility exists that contamination within the system produced the non-condensable gases during boiling.

Two possible sources of the contamination are conjectured. The first is that high temperatures on the heater tubes and poor circulation in the boiling chamber are combining to break down the refrigerant molecules producing some type of hydro-carbon. The second is that a chemical reaction is occurring between the refrigerants and gasket material in the apparatus producing a hydro-carbon. Time and funding limitations have prevented further investigation of the problem.

5. Summary

The original test plan called for the testing of various enhanced surfaces in a simulated bundle during condensation of R-114. The contamination problem described above, coupled with the time delays inherent in achieving solutions to the other aforementioned encountered problems, severely limited the results of this thesis.

B. DATA REDUCTION

1. Description of Program Capabilities

The computer program, DRP1F, that collects and processes raw data, in conjunction with a Hewlett-Packard computer/data acquisition system described in Chapter II, is listed in its entirety in Appendix C. The program is designed to calculate and plot heat transfer parameters for a variety of different tube bundles, utilizing R-114, R-113, or steam as the working fluid. The program has the added capability of allowing testing for single tube performance. The program consists of five main sections, as follows:

1. Driver Program,
2. Main Program,
3. Property Subroutines,
4. Modified Wilson Plot Subroutine.
5. Plotting Subroutines.

Of these five sections, only the modified Wilson Plot subroutine will be described in lengthy detail.

The driver program permits the user to take data, reprocess data, or plot re-processed data through various subroutines. The driver program is listed in lines 1000 through 1125, in Appendix C.

The main subroutine (lines 1130-2315) can be divided into five parts. The first part allows the user to select the physical parameters used in data reduction. The selection of parameters consists of the working fluid to be used (R-114, R-113, or steam), the vapor saturation temperature to be used (derived from averaged thermocouple readings in either the vapor section or liquid region of the apparatus), the instrumented test tube type, and whether data will be taken on a bundle or individual tubes. The second part allows the user to reprocess data with the same selection of physical parameters described above, but calls the modified Wilson Plot subroutine to calculate the inside and outside coefficients used in the correlations. Basic data reduction takes place in the third part (lines 1945-2125). Subroutines are called to calculate the properties of the ethylene glycol-water solution. These properties, with the physical tube dimensions, are used to calculate velocities and Reynolds numbers. Low coolant velocities and high viscosities prompted the use of twisted tape inserts (thickness 0.559 mm, with a pitch for a 180 degree twist of three times the tube's inner diameter) to increase the inside heat flux. The inside Nusselt number with a twisted tape insert, provided by Hong and Bergles [Ref. 21], is given by the correlation:

$$\overline{Nu}_i = \frac{\bar{\alpha}_i D_i}{\lambda} = 5.172[1 + 5.4838 \cdot 10^{-3} \cdot (Pr^{0.7}) \cdot (\frac{Re_s}{y})^{1.25}]^{1/2} \tag{4.1}$$

where the Reynolds number for coolant flow was given by:

$$Re_s = 4 \cdot \dot{\Gamma} / \pi \cdot \eta \cdot (D_i - 4\delta) \tag{4.2}$$

where, δ is tape thickness.

The outside heat transfer coefficient is then given by the well-known summation of resistances to heat transfer:

$$\frac{1}{U_o A_o} = \frac{1}{\bar{\alpha}_o A_o} + R_f + R_m + \frac{1}{\bar{\alpha}_i A_i} \tag{4.3}$$

which algebraically reduces to:

$$\bar{\alpha}_o = \frac{1}{\frac{1}{U_o} - R_m A_o - R_f A_o - \frac{1}{\bar{\alpha}_i}(\frac{A_o}{A_i})} \tag{4.4}$$

The heat transferred to the coolant (Q) is given by the relationship:

$$Q = \dot{\Gamma} \cdot C_p \cdot (\Delta T) \tag{4.5}$$

The heat flux (Q") is subsequently calculated by dividing by the outside surface area:

$$Q'' = \frac{Q}{A_o} \tag{4.6}$$

where $A_o = \pi \cdot D_o \cdot L$. And, the overall heat transfer coefficient (U_o) is given by:

$$U_o = \frac{Q''}{LMTD} \tag{4.7}$$

where the Log Mean Temperature Difference (LMTD) is defined to be:

$$LMTD = \frac{\Delta T}{\log\left[\frac{T_{sat}-Tc_i}{T_{sat}-Tc_o}\right]} \tag{4.8}$$

It should be noted that the wall resistance due to fouling was assumed to be negligible for the purposes of calculation.

The fourth part of the main subroutine creates a raw data file (lines 1680-1835), allowing subsequent reprocessing by the modified Wilson subroutine. The fifth part of the main subroutine provides a printed output both while taking initial data and subsequently after reprocessing data.

The third major section of the computer program calculates fluid properties through called functions for both the working fluid and the coolant. The calculated coolant properties as a function of temperature (lines 2330-2615), are kinematic viscosity, specific heat, density, Prandtl number, and conductivity.

The fifth major section of the program provides plotting routines for the output files generated in the program. The relationships graphically displayed are heat-transfer coefficient ratios (either based on the first tube in the bundle or as a ratio of the Nusselt value) plotted against tube position, heat transfer coefficient plotted against either the heat flux or temperature rise of the coolant, and the X-Y plot generated from the modified Wilson Plot results.

2. <u>Modified Wilson Plot</u>

The modified Wilson Plot, as outlined by Marto [Ref. 22], accomplishes an indirect measurement of the outside heat-transfer coefficient. The implicit assumption is that the overall heat transfer coefficient (U_o) is reliably known from data and, therefore a summation of heat transfer resistances is assumed. This summation relationship is given by:

$$\frac{1}{U_o} = \frac{1}{\alpha_o} + R_f A_o + R_m A_o + \frac{1}{\alpha_i}\left(\frac{A_o}{A_i}\right) \qquad (4.9)$$

where resistance due to wall fouling is assumed equal to zero. The summation equation is transformed to a linear relationship, as follows:

$$\left[\frac{1}{U_o} - R_m A_o\right] = \left(\frac{A_o}{A_i}\right)\frac{1}{\alpha_i} + \frac{1}{\alpha_o} \qquad (4.10)$$

where:

$$\overline{\alpha}_i = C_i\left(\frac{\lambda}{D_i}\right) \quad ; \quad \overline{\alpha}_o = C_o F \qquad (4.11)$$

which results in the simple linear form, Y = mX + b. It should be noted that Theta (defined in line 3290) is derived from the Hong and Bergles [Ref. 20] relationship for the inside Nusselt number, given by:

$$\overline{Nu}_i = \frac{\overline{\alpha}_i D_i}{\lambda} = C_i\left[1 + 5.4838\cdot 10^{-3}(Pr^{0.7})\cdot\left(\frac{Re_s}{y}\right)^{1.25}\right]^{1/2} \qquad (4.12)$$

hence,

$$\theta = \left[1 + 5.4838\cdot 10^{-3}(Pr^{0.7})\cdot\left(\frac{Re_s}{y}\right)^{1.25}\right]^{1/2} \qquad (4.13)$$

Further, F (defined in line 3330), is derived from Nusselt's relationship for a horizontal cylinder subjected to a constant heat flux [Ref. 4], given by:

$$\overline{\alpha}_o = .655\left[\lambda^3\cdot\rho^2\cdot g\cdot\Delta h_v/\eta\cdot D_o\cdot Q''\right]^{1/3} \qquad (4.14)$$

Hence,

$$F = \left[\lambda^3\cdot\rho^2\cdot g\cdot\Delta h_v/\eta\cdot D_o\cdot Q''\right]^{1/3} \qquad (4.15)$$

X and Y values are calculated from raw data and the data are fit with a least squares approximation. Initial assumed values are taken from the aforementioned correlations, and the solutions iterated to find the inside coefficient (C_i) and the outside coefficient (C_o) that fit the data, where:

$$Y = [\frac{1}{U_o} - R_m(A_o)]F \; ; \quad X = \frac{D_o \cdot F}{\lambda} \tag{4.16}$$

the slope (m) is given by:

$$m = \frac{1}{C_i}$$

and the intercept (b) is given by:

$$b = \frac{1}{C_o}$$

The accuracy of this method relies heavily upon the number of data points taken and the range of velocities utilized.

V. RESULTS AND DISCUSSION

A. EXPERIMENTAL SEQUENCE

The data runs are summarized in Table 5.1 according to tube type, refrigerant used, and approximate operating parameters. Specifics for each run are provided in the following section under the run title.

TABLE 5.1

SEQUENTIAL LISTING OF DATA RUNS

Run Title	Tube Type	Refrigerant Used	Coolant T inlet	Vapor T saturation
SMT02	smooth	R-114	-20 C	17.8 C
CNFT01	finned	R-114	-21 C	18.3 C
CNFT02	finned	R-113	-21 C	64.4 C
CNFT03	finned	R-113	-3 to +6 C	52.2 C
CNFT04	finned	R-113	-3 to +6 C	46.3 C
SMT03	smooth	R-113	-1 to +6 C	56.7 C

B. EXPERIMENTAL RESULTS

1. Smooth Tubes with R-114 and Low Coolant Temperature

SMT02 was an experimental run made with four smooth copper tubes while condensing R-114. Vapor saturation temperature was 17.8 C. Ambient temperature was 20 C. The ethylene glycol coolant inlet temperature was -20 C. The experiment was conducted following a cleaning of the boiling chamber, two flushings of the apparatus, once with acetone and once with R-113, evacuation to 27.5 in Hg., and filling the system from an unopened cylinder of R-114. After filling the system, the apparatus pressure stabilized at 17 psig. The system pressure was lowered to 10 psig by opening the coolant flow through the auxiliary condenser. When the desired gage pressure was reached, the lowest flow rate was set through the instrumented tube bundle, and all three heater units were set for power levels corresponding to approximately 10 kW total. Gage pressure was maintained nearly constant by controlling coolant flow through the auxiliary condenser. The system required approximately 35 minutes from lightoff to reach a steady state condition, indicated by nearly constant gage pressure. The R-114 appeared clear at the commencement of the data run. By the time the apparatus reached a steady state condition, the contamination matrix was fully formed and visible on the top two tubes in the bundle. Data were taken at nine different coolant velocities, after the voltage indicator on the data acquisition system for the bottom tube thermopile appeared to reach a fixed value following each velocity change. Data for the tube bundle run (Figure 5.1) clearly demonstrates an observed uncertainty of about 7% in the overall heat transfer coefficient (U_o) at velocities close to 0.9 m/s. This observed uncertainty, in contrast to the maximum calculated uncertainty of 4.5% (see Appendix A),

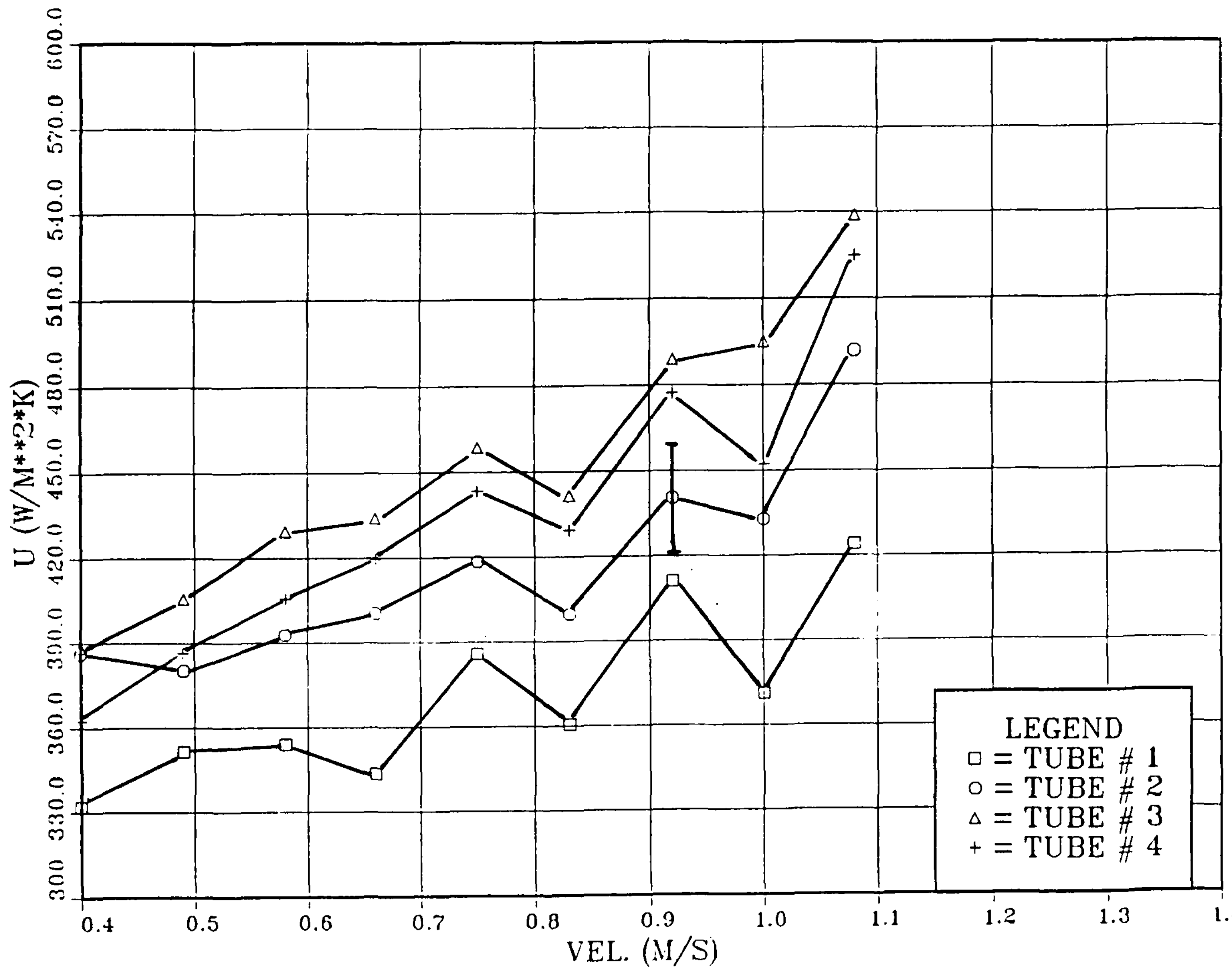

Figure 5.1 SMT02--Tube Bundle Performance

indicates the effect of the contamination on the measurement of the overall heat transfer. The most significant result of the contamination is the addition of an un-quantifiable resistance to heat-transfer that has produced heat-transfer coefficients approximately half of those predicted by the Nusselt correlation. Further, it is apparent that during bundle operation, the contamination degrades the performance of the tubes in a graduated manner with the first tube being the most adversely affected and the third tube appearing the least affected.

Upon completion of the bundle run, the flow in all of the instrumented tubes was shut off. Gage pressure was maintained at 10 psig by controlling coolant flow through the auxiliary condenser. The coolant inlet temperature remained approximately -20 C. The apparatus remained in this condition until the tube surfaces appeared to dry off, which took normally about ten minutes. Data were then taken at the same nine flow rates, as for the bundle, but with flow through only one instrumented tube at a time, starting with the top tube. Between velocity changes, approximately 10 minutes was allowed for the temperature changes in the tube to take effect. Data runs were made only after inundation from the previously tested tube was no longer present. The R-114 in the boiling chamber remained visually clear for all single tube runs. Again, as in the bundle data, data from the single tube runs (Figure 5.2) fall within an acceptable uncertainty band.

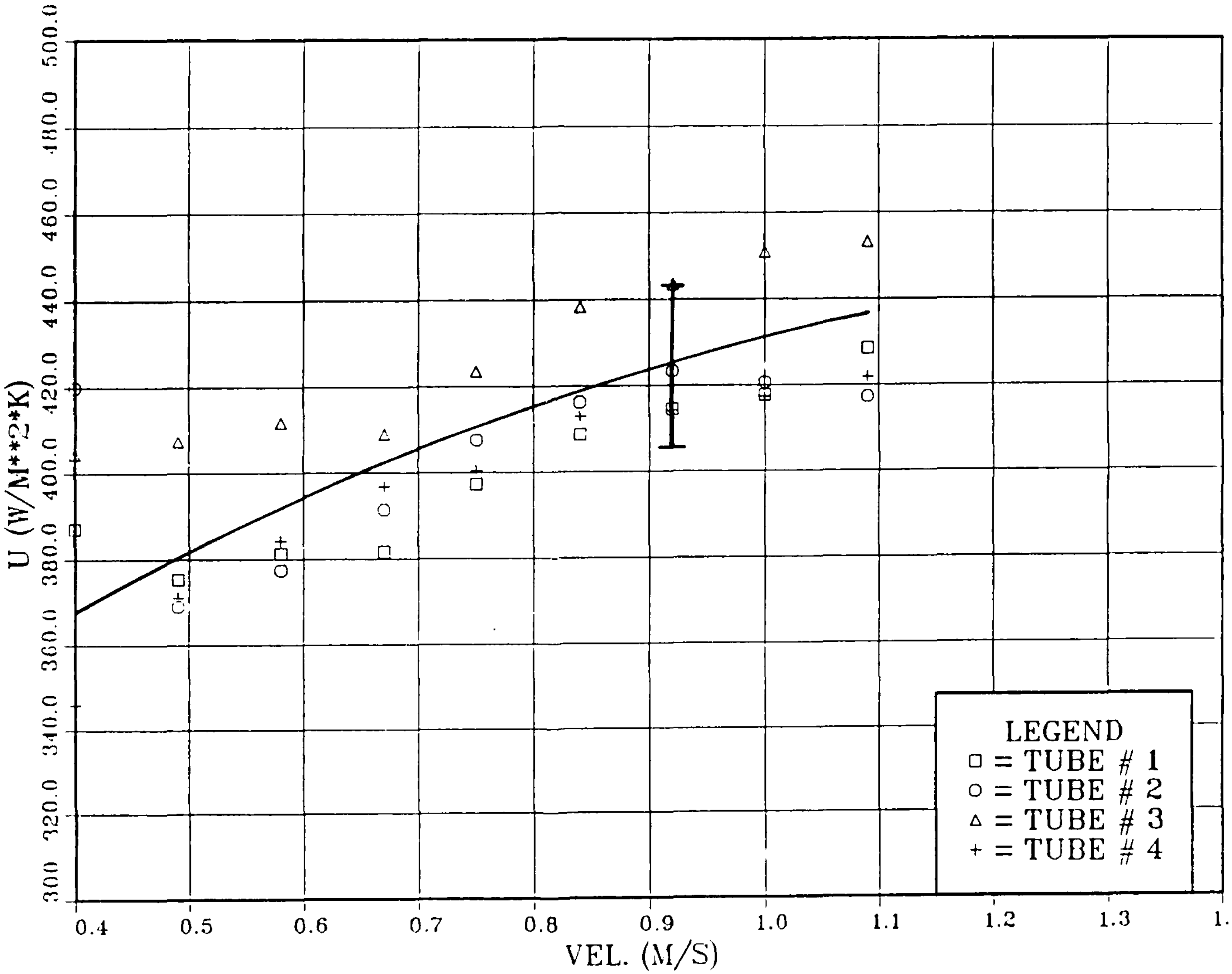

Figure 5.2 SMT02--Individual Tube Performance

From the conditions under which these runs were made, it is noteworthy and logical that the effect of the contamination increases in magnitude as a run progresses. The first tube gives the lowest results possibly because of residual contamination from the bundle run. The first and second tubes produced approximately the same results as previously discussed in the bundle run, however the third and fourth tubes gave lower results when operating as single tubes than when operating in a bundle, possibly because condensate inundation that provides a rinsing effect in the bundle operation,is no longer present during single tube operation.

2. Finned Tubes with R-114 and Low Coolant Temperature

CNFT01 was an experimental run made with copper-nickel low integral-fin tubes condensing R-114. Vapor saturation temperature was 18.3 C. The ethylene glycol coolant inlet temperature was at -21 C. The experiment commenced following the completion of the SMT02 single tube runs, transfer of the R-114 to the auxiliary storage unit, installation of the copper-nickel finned tubes, evacuation of the apparatus to 27.5 in Hg, and a refill of R-114 from the storage unit. This process took approximately six hours to complete. The same data taking procedure as outlined for the smooth tube runs was followed. The appearance of the R-114 was clear at the commencement of the run. By the time the system reached steady state, a marked thickening of the fin areas on the top tube when compared to the fins of the second tube was apparent (see Figure 4.1). The R-114 appeared clear at the end of the bundle run. Data from the bundle run (Figure 5.3) show an increase in the overall heat transfer coefficient of approximately 100% when compared to the bundle results for the smooth tubes SMT02 (Figure 5.1). The coolant velocity differences between the smooth tubes and the finned tubes is due to the smaller inside diameter of the finned tubes at the prescribed mass flow rate. There is no disparity between calculated and observed uncertainties given the calculated uncertainty band, but performance remains approximately half of that expected when compared to the values obtained with the Nusselt correlation and enhancement ratios reported by other investigations. Once again,the first and second tubes demonstrate the greatest degradation in performance due to the contamination. The third and fourth tubes either receive less contamination or derive enhancement from condensate inundation flow. From observations, the unknown contaminant had a higher surface tension than R-114, but to what extent the contaminant kept fin root areas flooded and subsequently negated the enhanced surface effect, remains obscured in the uncertainties of the measurements.

The single tube runs followed the procedures outlined for the single tube runs of the smooth copper tubes. However at the end of each single tube run, a marked thickening of the fin surface at the top of the tube was noticeable. Vapor saturation temperature and coolant inlet temperature were the

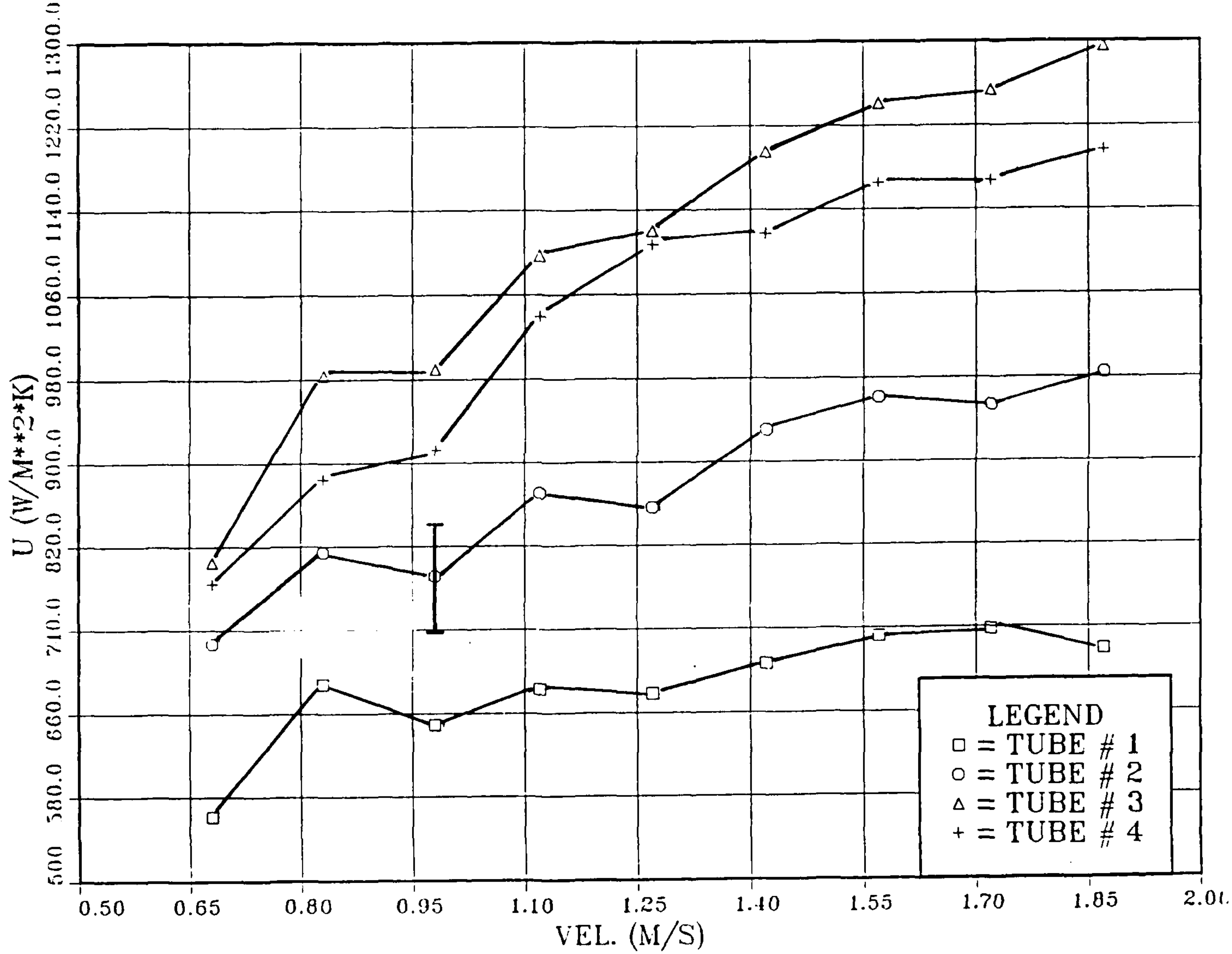

Figure 5.3 CNFT01--Tube Bundle Performance

same as in the bundle run. Data from the single tube runs (Figure 5.4) demonstrate an enhancement of approximately 76% in the overall heat transfer coefficient when compared to its counterpart in SMT02. The spread in the data is approximately 7% and, given the calculated uncertainty band, appears reasonable. Performance remains lower than expected from existing studies, and clearly the magnitude of the contamination effect increases as each run proceeded.

3. <u>Finned Tubes with R-113 and Low Coolant Temperature</u>

Upon completion of the single tube runs described in CNFT01, R-114 was transferred to the storage unit. The apparatus was drained of residual refrigerant, the system was evacuated to 27.5 in Hg, and filled with freshly distilled R-113 by using apparatus vacuum to promote flow from the R-113 container. After filling, system vacuum was at 11 inches Hg. The system was brought to a gage pressure of 5 psig corresponding to a vapor saturation temperature of 64.4 C. Coolant inlet temperature remained the same as described in CNFT01, -21 C. Vapor saturation temperature was monitored through the system pressure, and controlled by regulating coolant flow through the auxiliary condenser. The same nine data points described previously were taken in accordance with the stated procedure. The appearance of the R-113 at the beginning of the run was clear and clean. Upon the conclusion of the run, however, the R-113 had a slight yellowish tinge. During the run, the same marked thickening of the fin surface

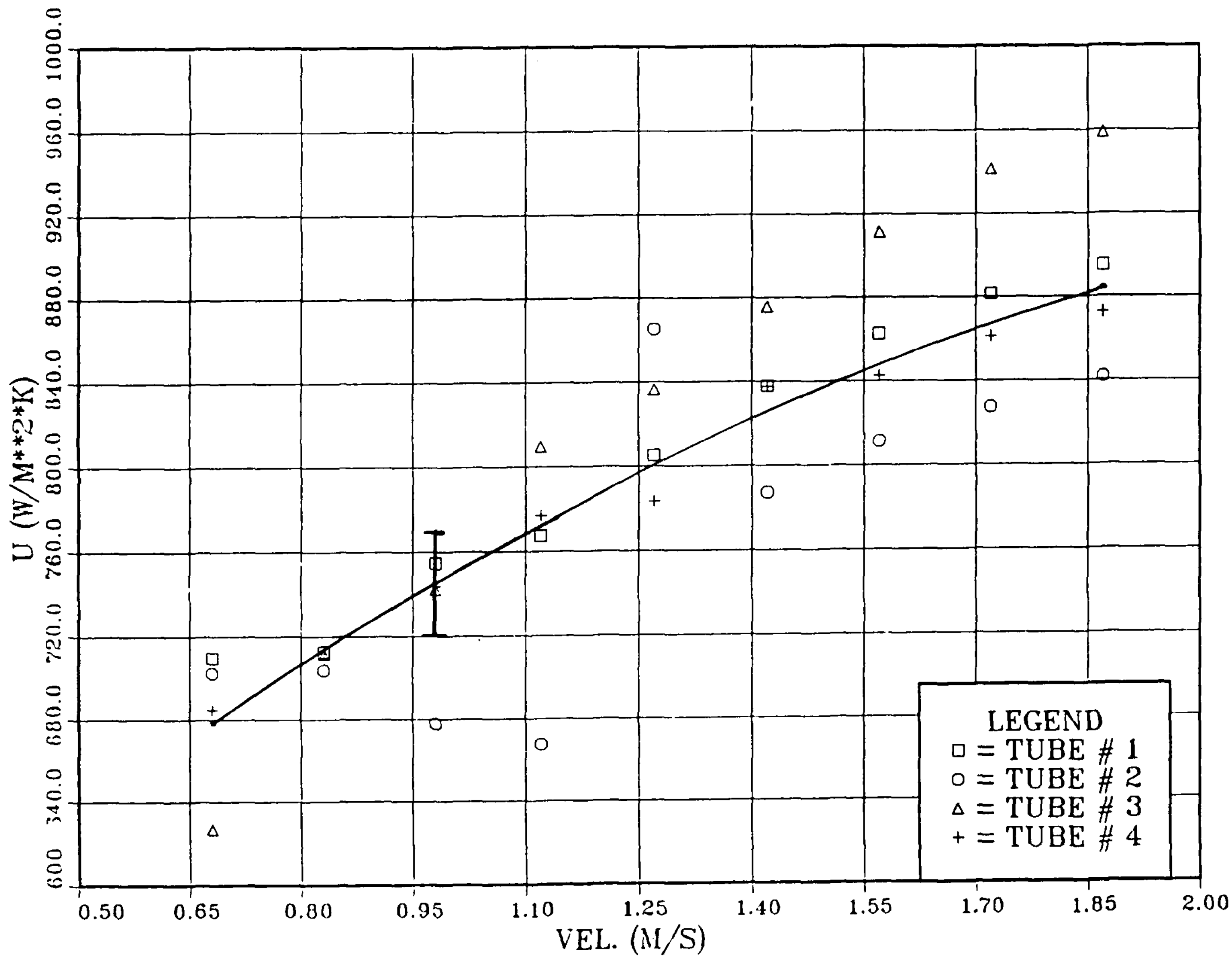

Figure 5.4 CNFT01--Individual Tube Performance

described in CNFT01, and shown schematically in Figure 4.1 occurred on the top tube. The data from the bundle run (Figure 5.5) demonstrates only a slight improvement in the overall heat transfer coefficient when compared to the bundle data for SMT02 (Figure 5.1), and in fact represents an approximate 80% decrease in the overall heat transfer coefficient when compared to the performance of the bundle in CNFT01 (Figure 5.3). In view of the fact that these data were collected after transferring the R-114 to the storage unit and filling with freshly distilled R-113, it can only be assumed that the contamination was freshly created with the R-113 and, in fact is associated with the apparatus. It is also possible, based on these results, to infer the presence of non-condensable gases generated by the contamination, although no indications of non-condensable gases were detected during the run. In view of these facts, the reliability of the calculated values for the overall heat transfer coefficient is extremely doubtful even though data spread falls within the acceptable uncertainty band.

Upon completion of the bundle run, data were taken for each of the tubes individually at the same system conditions described for the bundle run, and in accordance with the procedure described for single tube runs. The appearance of the R-113 at the completion of the single tube runs was slightly-darkened, with a yellow tinge, but otherwise appeared free from any floating contaminants. On each of the single

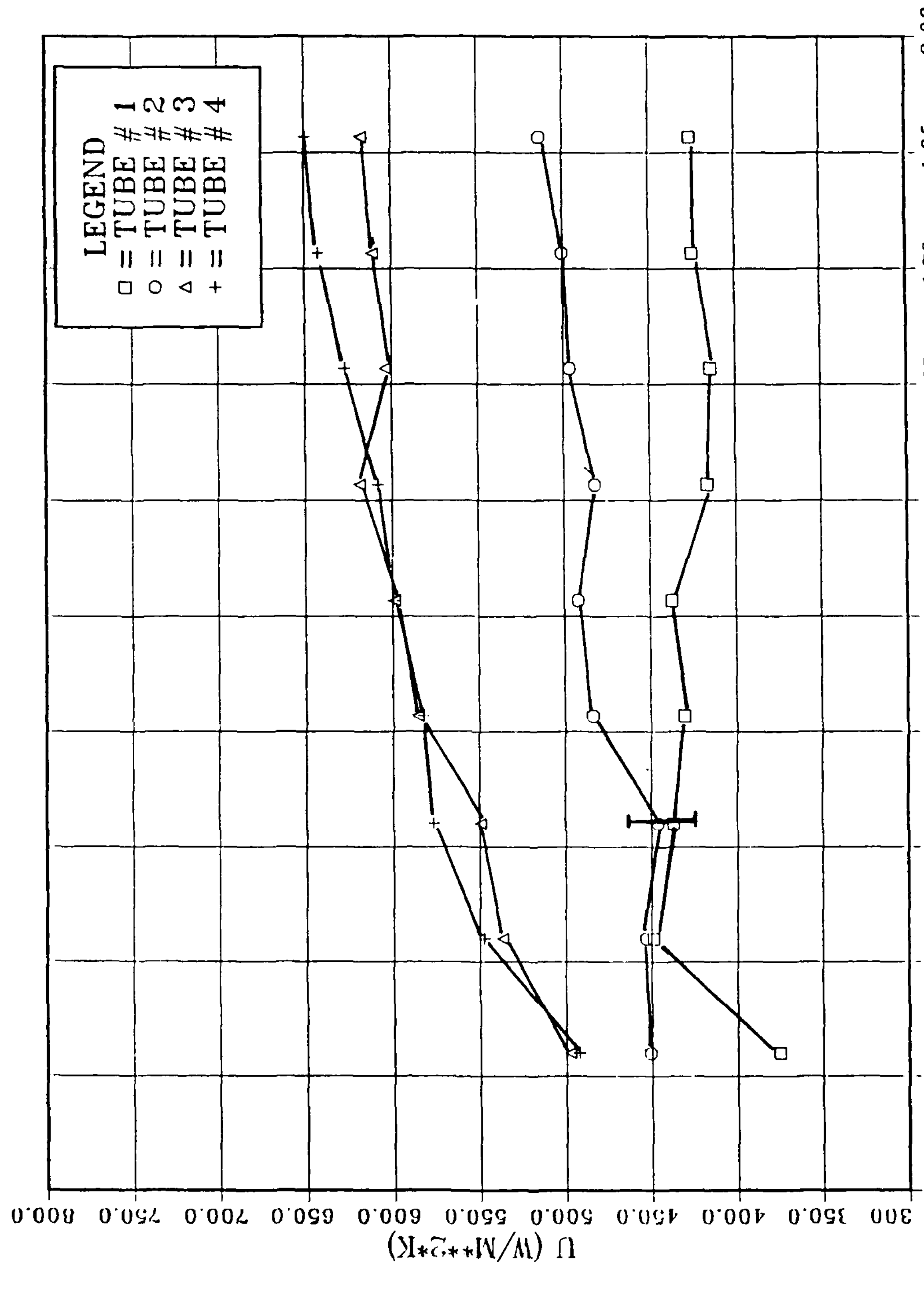

Figure 5.5 CNFT02--Tube Bundle Performance

tube runs, a marked thickening of the fin surface developed in the course of the run. There exists reasonably good agreement between the single tube data (Figure 5.6) and the single tube data from CNFT01 in the calculation of the overall heat transfer coefficient, and no disparity exists between the data spread and the calculated uncertainty band. The apparatus was evacuated for five minutes prior to beginning the single tube runs and if non-condensable gases were present during the bundle run, this explains the improved performance of the tubes during individual runs.

4. <u>Finned Tubes with R-113 and High Coolant Temperature</u>

This data run was made with the same copper-nickel tubes described in CNFT01 and CNFT02. The system was allowed to sit overnight at 11 in Hg, while the sump temperature was brought to an operating range of -3 C to +6 C. No change in the system vacuum over this 12 hour period occurred. The decision to run the system at a higher coolant temperature was motivated by a belief that the contamination of the system was water, and that at the colder coolant temperature, an ice sheath was forming on the tubes inhibiting heat transfer. The appearance of the R-113 before commencement of the bundle run was a medium yellow tinge. The system was brought to a steady state pressure corresponding to a vapor saturation temperature of 52.2 C. Difficulty was encountered in maintaining positive system pressure with the auxiliary condenser operating. The auxiliary condenser was therefore turned off and steady state

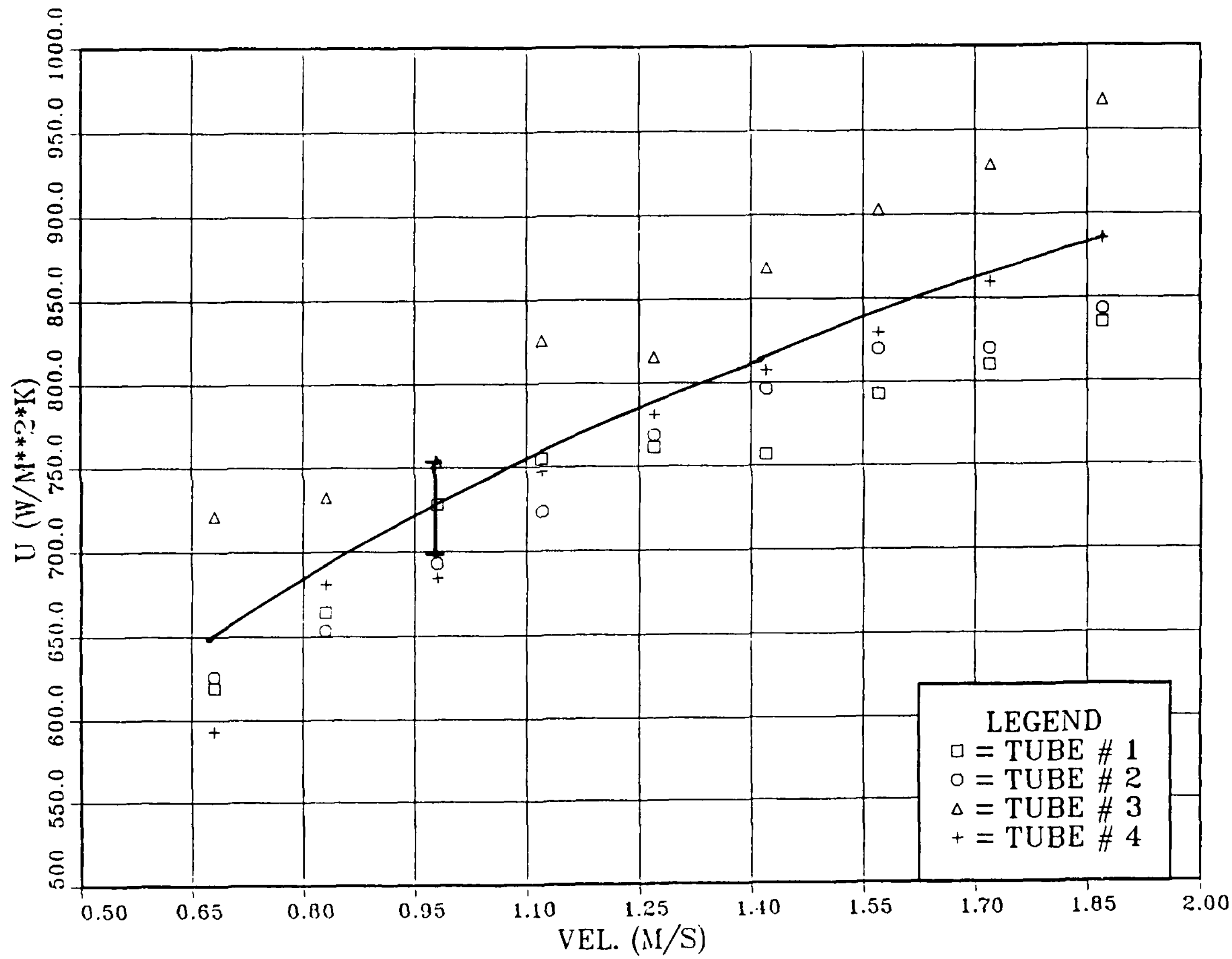

Figure 5.6 CNFT02--Individual Tube Performance

was maintained by slight power adjustments to the heating elements in the boiling chamber. Nine sets of data were taken in accordance with the procedure for bundle runs previously described. No observable thickening of fin surfaces during the run occurred. The data from the bundle run (Figure 5.7) shows a slight increase in overall heat transfer coefficient over the bundle results obtained in CNFT02 (Figure 5.5) and this is possibly explained by a decrease in the viscosity of the contaminant when exposed to the warmer tube surface.

Single tube runs were made on each of the tubes, in accordance with procedures outlined previously, at the same coolant inlet temperature as in the bundle run, but at a system pressure corresponding to a vapor saturation temperature of 64.4 C. No change in the appearance of the R-113 was detected. Again no thickening of the fin surfaces was detected. The single tube results (Figure 5.8) demonstrate a corresponding range of values in the overall heat transfer coefficient when compared to the results for single tubes in CNFT02 (Figure 5.6), but is significantly higher than the bundle results. It is possible that non-condensable gases were present in bundle operation, but were eliminated by evacuation prior to single tube data being taken. No indications of non-condensable gases were detected during bundle or single tube operation.

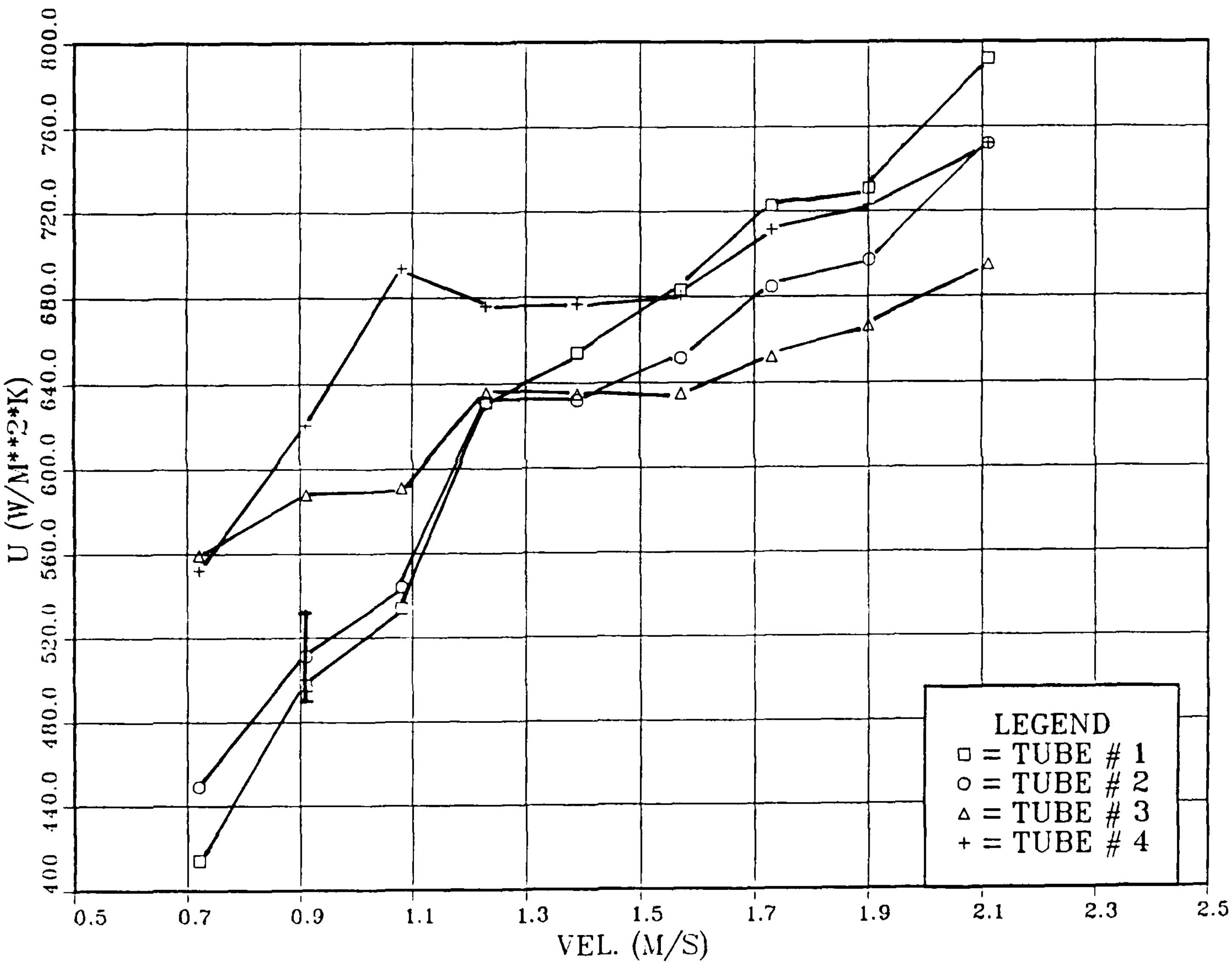

Figure 5.7--CNFT03--Tube Bundle Performance

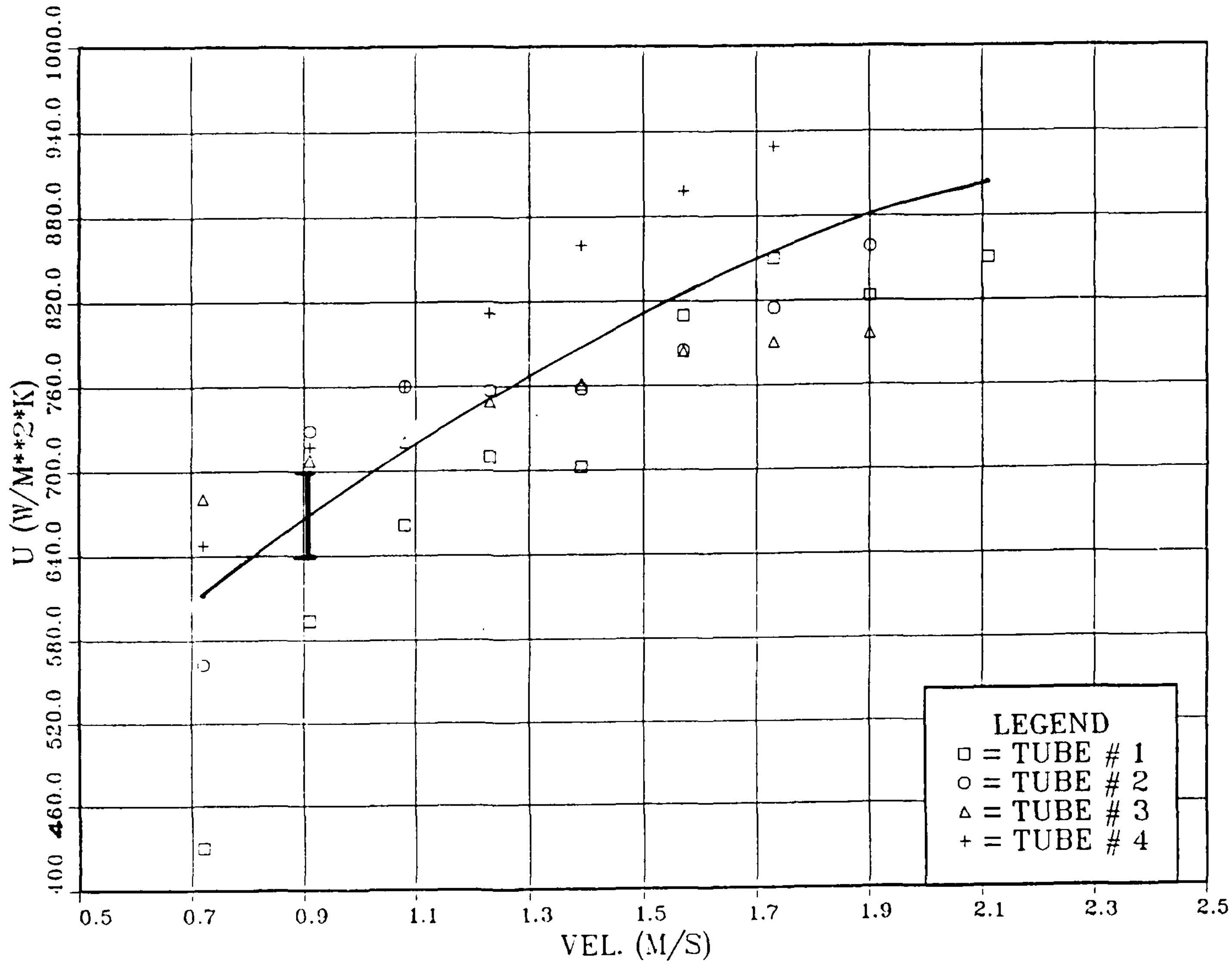

Figure 5.8--CNFT03--Individual Tube Performance

5. <u>Finned Tubes with R-113 and High Coolant Temperature</u>

This data run was made in order to see if the results produced in CNFT03 were repeatable. The system operating pressure corresponded to a vapor saturation temperature of 46.3 C, and the coolant inlet temperature remained unchanged from the coolant temperature in CNFT03. Nine data sets were taken in accordance with the bundle run procedures outlined previously. No thickening of fin surfaces during the run was observed. The color of the R-113, at the completion of the run, was amber. The bundle data (Figure 5.9) does demonstrate that the results of CNFT03 were repeatable at least within the calculated uncertainty.

Single tube runs were made in accordance with the procedures discussed previously. Nine data sets were taken on each tube, at the same conditions specified in the bundle run. No thickening of fin surfaces was observed during the runs, and the R-113 color remained amber. There is no major disparity between the single tube results (Figure 5.10), and the single tube results for CNFT03, given the calculated uncertainty band. The single tube results were significantly higher than bundle performance, and the build up of non-condensable gases during bundle operation and evacuation of the apparatus prior to commencing single tube runs is conjectured as a possible explanation. At no time during bundle or single tube operation were indications of non-condensable gases detected.

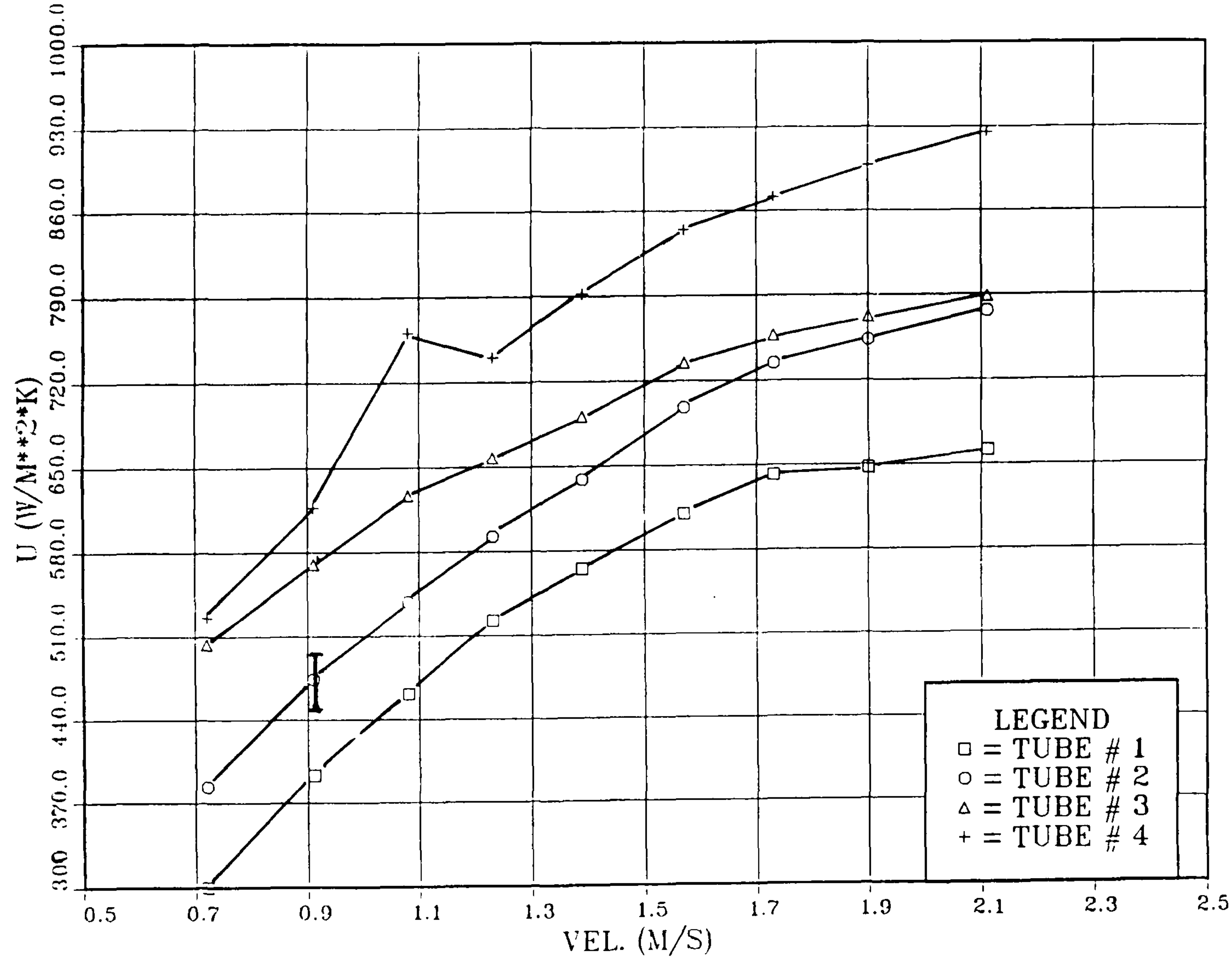

Figure 5.9--CNFT04--Tube Bundle Performance

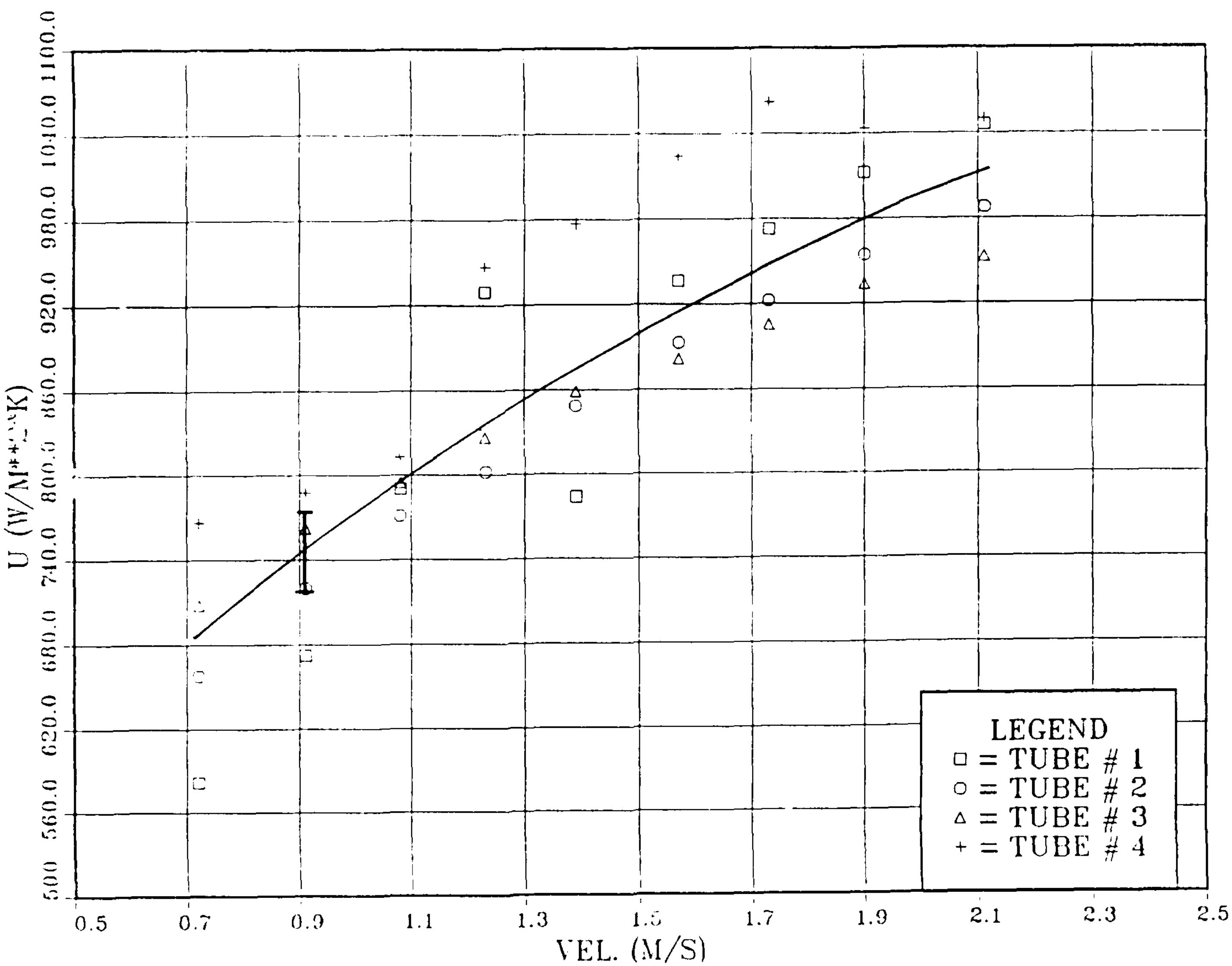

Figure 5.10--CNFT04--Individual Tube Performance

6. Smooth Tubes with R-113 and High Coolant Temperature

SMT03 was a data run made on the same aforementioned copper tubes, but with R-113. Vapor saturation temperature was 56.7 C. Coolant inlet temperature ranged between -1 C and +6 C. The experiment was conducted following a test run with R-113 and finned tubes and subsequent replacement of the finned tubes, and evacuation to 11 in Hg. While the tube change was being made, the R-113 remained in the boiling chamber exposed to the atmosphere for a two hour period. The R-113 appeared light amber in color at the commencement of the bundle run. The desired gage pressure was maintained by controlling the boiling chamber heaters through their corresponding variac controllers. The auxiliary condenser was not utilized because the additional coolant flow provided by the auxiliary condenser made it difficult to maintain the desired system pressure. During the data run, the top two instrumented tubes assumed an orange peel textured or dimpled appearance. The R-113 had a darker amber appearance at the completion of the bundle run. Again, data were taken at the same nine coolant flow settings following the procedure outlined previously. Data taken during bundle operation (Figure 5.11), while falling within the acceptable uncertainty bands, clearly demonstrates the presence of non-condensable gases as well the presence of the contamination acting to inhibit the overall heat-transfer performance. The top tube's very poor performance can be attributable to its location in

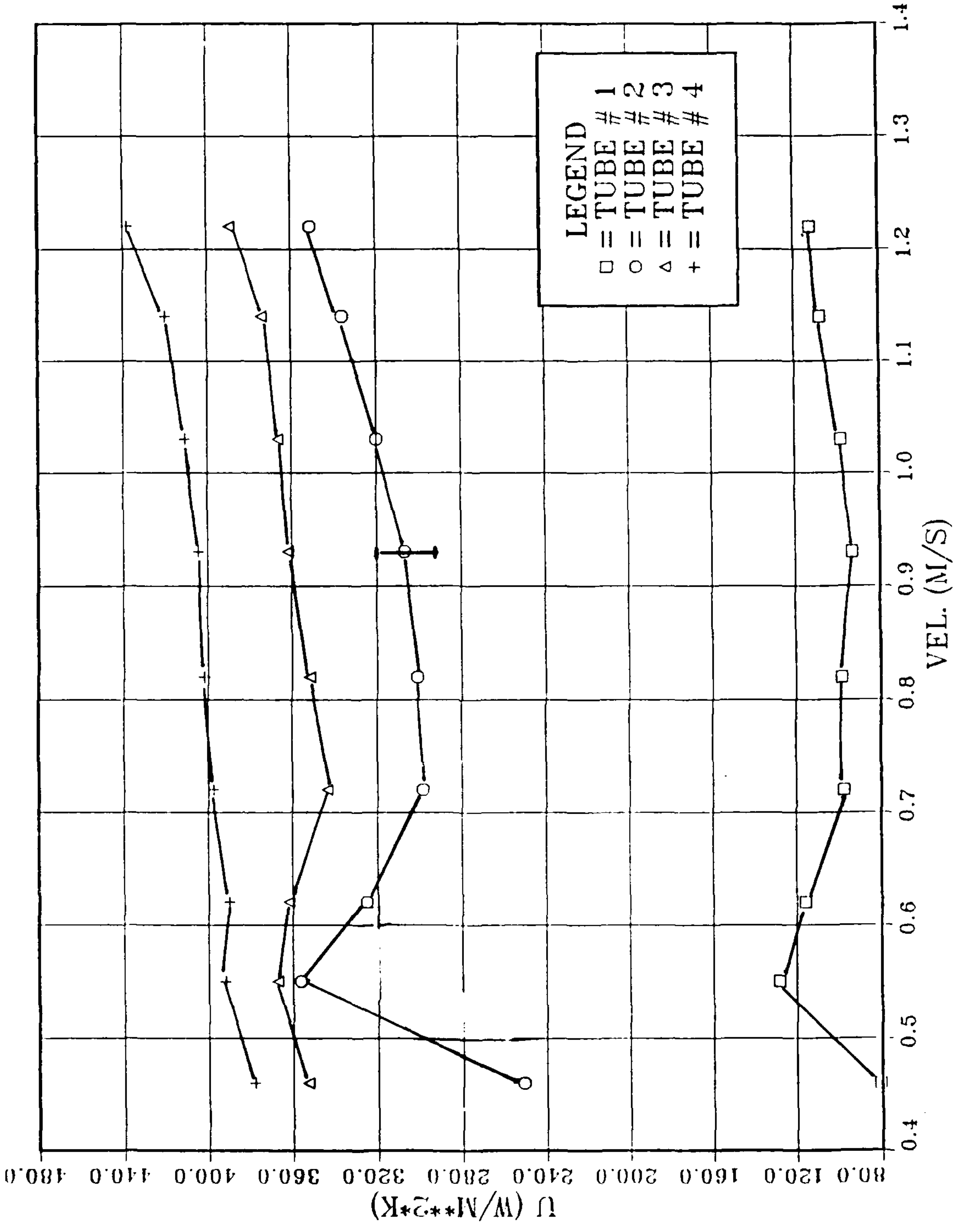

Figure 5.11--SMT03--Tube Bundle Performance

a pocket of non-condensable gases. And the bundle performance as a whole, when taken in comparison with the performance demonstrated in the bundle run of SMT02, indicates an increased concentration of the contamination and the presence of non-condensable gases.

Upon completion of the bundle run, coolant flow through the instrumented tubes was shut off and gage pressure maintained by controlling flow through the auxiliary condenser. While no coolant flowed through the instrumented tubes, the textured appearance noted during the bundle operation gradually transformed to small droplets on the top two tubes which then coalesced into larger ellipsoid shaped droplets that were held on the tube by surface tension forces. Data was taken on the first two tubes in the bundle following the procedure outlined previously for single tube runs. At the completion of the second run, it was noticed that the top view port flanges were cold to the touch while the bottom view port flanges were warm to the touch. The assumption was therefore made that non-condensable gases had collected in the top of the condensing chamber. Before evacuation of the apparatus could be effected, the pyrex glass in the top center view port cracked. As a result, the apparatus was secured and no further data taken. It should be noted that, prior to the view port breaking, there was no evidence to suggest that the apparatus was other than air tight, so that the source of non-condensable gases was most probably due to their generation within the boiling chamber. Data taken in the single tube runs (Figure 5.12) reflects not only the effects of the contamination, but also the effects of the presence of non-condensable gases as well. This data showed the greatest variance between calculated and observed uncertainties in the overall heat transfer coefficient. This data is limited to the performance of only the top two tubes, due to the aforementioned breakage of the view port and the presence of non-condensable gases.

C. SUMMARY OF RESULTS

The comparison between finned and smooth tubes shows an enhancement ratio in the overall heat transfer coefficient for the finned tubes compared to the smooth tubes of approximately 2.0. While this enhancement in the overall heat-transfer coefficient might translate to a vapor-side heat-transfer coefficient enhancement ratio of approximately 4.0 to 4.5, based upon the calculated values for the vapor-side heat-transfer coefficient for the tested smooth tubes when compared against the Nusselt's correlation for smooth horizontal tubes and the reported enhancement ratios from other finned-tube investigations [Refs. 5-13], it is estimated that the effect of the contamination during these tests has been a degradation of up to 50% in the vapor-side heat-transfer coefficient. The contamination has resulted in the promotion of another resistance to heat transfer that has no predictable characteristics and can not be quantified. This contamination

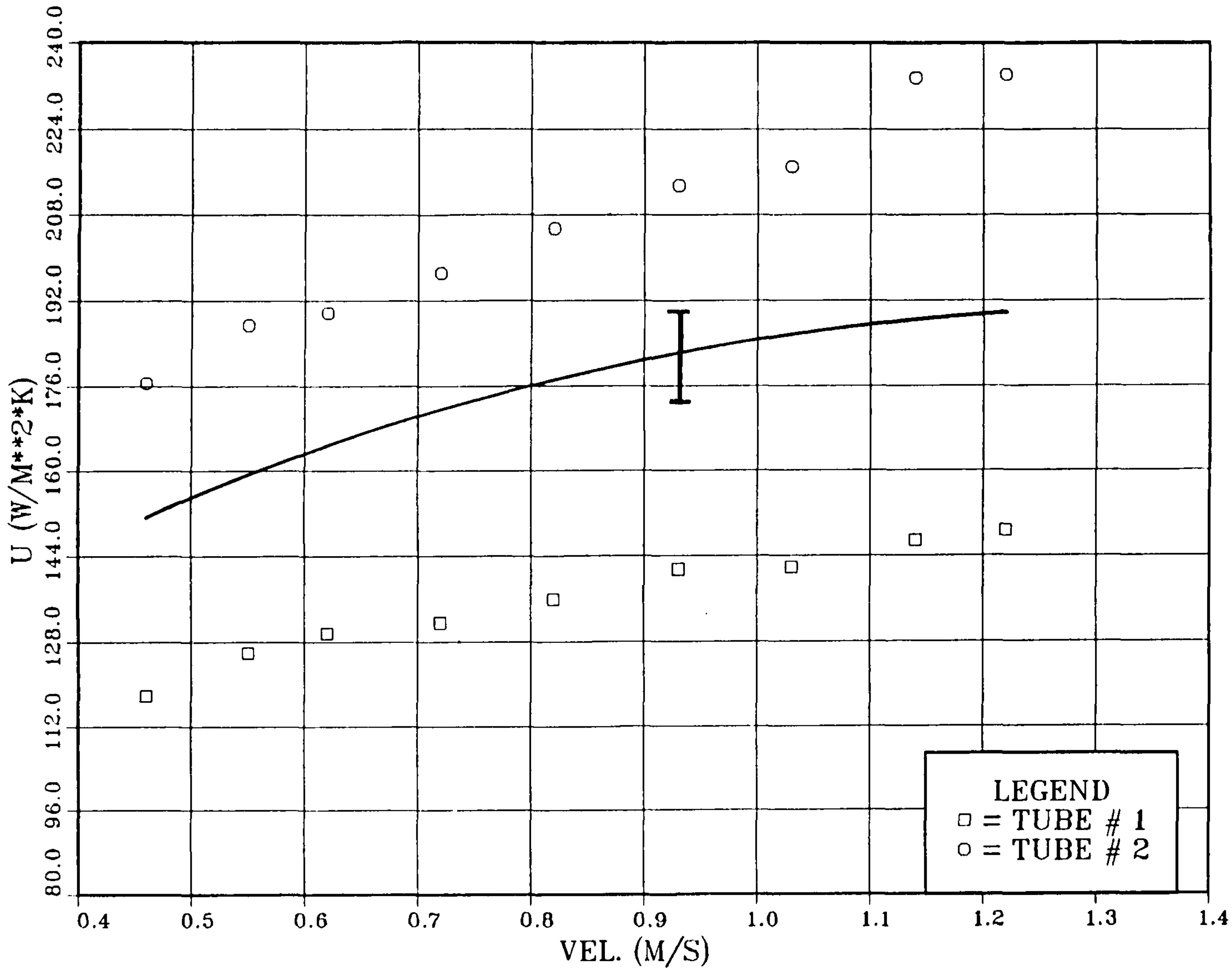

Figure 5.12--SMT03--Individual Tube Performance

must therefore be removed before any quantifiable heat-transfer results can be obtained.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Based on the data gathered during this investigation for condensation of refrigerants R-114 and R-113 in the multi-tube apparatus, the following conclusions are reached:

1. The construction of a multi-tube condensation test apparatus begun by Murphy [Ref. 3] and Zebrowski [Ref. 4] has been completed, instrumented and integrated with the various support systems.

2. Data reduction software has been developed that produces high confidence results from experimental readings.

3. Data were collected from condensation experiments with R-114 and R-113 on smooth and finned tubes demonstrating an enhancement ratio of approximately 2.0 in the overall heat transfer coefficient for the finned tubes over the smooth tubes.

4. Serious apparatus internal contamination has degradated the value of the overall heat-transfer beyond acceptable limits, making further data reduction meaningless.

B. RECOMMENDATIONS

Based upon the data gathered during the operation of the multi-tube condensation test apparatus, and the experience gained in construction of this apparatus, the following recommendations are made:

1. Samples should be taken from the R-114 and R-113 used in the experimental runs and a chemical analysis performed on these samples to assist in determining the source of the contamination in the system.

2. Modifications to the apparatus, as dictated by the results of the chemical analysis of the refrigerants, should be made.

3. New flow meters allowing a greater range in coolant velocities should be installed. The greater range in coolant velocities will enhance the accuracy of the modified Wilson plot method in calculating the outside heat-transfer coefficient.

4. The temperature control system for the eight ton refrigeration unit should be re-evaluated to determine if tighter control of sump temperature can be maintained.

5. After appropriate modifications to the apparatus have been made, the smooth tube and finned tube experiments should be repeated and contrasted with the results presented here, in order that baseline tube performance might be established.

6. During operation of the system, flow should be throttled to the coolant supply pumps with the valves on the coolant inlet side. This will increase the pump life and reduce noise in the laboratory space.

APPENDIX A

UNCERTAINTY ANALYSIS

A certain amount of uncertainty exists in any engineering measurement. These uncertainties arise both from known sources, such as calibration and measurement errors from sensing devices, and also unknown sources, such as operator experience and unexpected experimental reactions. The procedure used in this uncertainty analysis is based on the Kline-McClintock [Ref. 21] method. This method assumes that a result R is a function of the variables that contribute to that result. Therefore the uncertainty in a result is a function of the uncertainties in each of the variables. This method is expressed mathematically by:

$$\frac{\partial R}{R} = \left[\left(\frac{\partial R}{\partial V_1} \cdot \frac{\partial V_1}{R}\right)^2 + \left(\frac{\partial R}{\partial V_2} \cdot \frac{\partial V_2}{R}\right)^2 + \ldots \right]^{1/2} \qquad \text{(A.1)}$$

The measurement of the overall heat transfer coefficient (U_o) performed in this thesis is given by:

$$U_o = \frac{Q}{A_o \cdot LMTD} \qquad \text{(A.2)}$$

where the heat transferred (Q) is given by:

$$Q = \dot{m} \cdot C_p \cdot (\Delta T) \qquad \text{(A.3)}$$

and the Log Mean Temperature Difference (LMTD) is defined as:

$$\mathrm{LMTD} = \frac{(\Delta T)}{\log\left[\frac{T_{sat}-Tc_i}{T_{sat}-Tc_o}\right]} \tag{A.4}$$

Therefore the uncertainty in the measurement of the overall heat transfer coefficient (U_o) is given by:

$$\frac{\delta U_o}{U_o} = \left[\left(\frac{\delta\dot{T}}{\dot{T}}\right)^2 + \left(\frac{\delta C_p}{C_p}\right)^2 + \left(\frac{\delta\Delta T}{\Delta T}\right)^2 + \left(\frac{\delta D_o}{D_o}\right)^2 + \left(\frac{\delta \mathrm{LMTD}}{\mathrm{LMTD}}\right)^2\right]^{1/2} \tag{A.5}$$

where $\frac{\delta A_o}{A_o}$ reduces to $\frac{\delta D_o}{D_o}$, and the uncertainty in the LMTD is given by:

$$\frac{\delta \mathrm{LMTD}}{\mathrm{LMTD}} = [A^2 + B^2 + C^2]^{1/2} \tag{A.6}$$

where A is given by the expression:

$$A = \delta T_{sat}\left[\frac{\Delta T}{(T_{sat}-Tc_i)(T_{sat}-Tc_o)} \cdot \frac{1}{\log\left[\frac{T_{sat}-Tc_i}{T_{sat}-Tc_o}\right]}\right]$$

where B is given by the expression:

$$B = \frac{\delta Tc_i}{(T_{sat}-Tc_i)} \cdot \frac{1}{\log\left[\frac{T_{sat}-Tc_i}{T_{sat}-Tc_o}\right]}$$

where C is given by the expression:

$$C = \frac{\delta Tc_o}{(T_{sat}-Tc_o)} \cdot \frac{1}{\log[\frac{T_{sat}-Tc_i}{T_{sat}-Tc_o}]}$$

It should be noted that the uncertainties for mass flow rate ($\dot{\Gamma}$) and the coolant temperature rise across the condensing tubes (ΔT) were calculated during calibration of the flow meters and thermopiles respectfully. Reference material providing data on thermophysical properties, specifically the specific heat (C_p), listed no uncertainties associated with the curves for aqueous-ethylene glycol solutions. The composition of the aqueous-ethylene glycol solution by weight percentages was calculated by measurement of the specific gravity and the change in this composition over the experimental period was determined to be negligable and therfore this uncertainty has been ignored.

The uncertainty in the overall heat transfer coefficient represents the maximum uncertainty present from the calibration of the four flow meters and the maximum uncertainty in the calibration of the four thermopiles, regardless of association, and therefore represents a conservative estimate of the uncertainty present in each calculation of the overall heat transfer coefficient (U_o). This maximum uncertainty was calculated to be 4.5 percent.

The disparity between the calculated uncertainties and the uncertainties observed by the spread in data particularly in the single tube runs, can be accounted for by the as-yet undetermined chemical or phase reactions generated by the contamination in the system.

The values of the uncertainties in the measured variables that were used to calculate the uncertainty by the Kline-McClintock method are listed in Table A.1.

TABLE A.1

UNCERTAINTY VARIABLES

VARIABLE		VALUE	REMARKS
$\frac{\delta \dot{\Gamma}}{\dot{\Gamma}}$		0.01	From flow meter calibration data
$\frac{\delta C_p}{C_p}$		0.00	Not available
$\frac{\delta \Delta T}{\Delta T}$		0.01	From thermopile calibration data
$\frac{\delta D_o}{D_o}$		0.002	From micrometer name plate data
$\frac{\delta LMTD}{LMTD}$			Listed below by run title
	SMT02		0.005
	CNFT01		0.002
	CNFT02		0.001
	CNFT03		0.003
	CNFT04		0.002
	SMT03		0.017

APPENDIX B

LIGHTOFF AND SECURING PROCEDURES

A. SYSTEM LIGHTOFF

1. Push the starter button in the control box for the re-circulation pump. This control box is located on the bulkhead above the re-circulation pump in the outside area adjacent to the refrigeration unit.

2. Turn the switch on the refrigeration unit control panel, located in front of the refrigeration unit to the "auto" position after passing through "on" position.

3. Set the desired temperature on the roughly graduated Fahrenheit scale on the control panel thermostat. It requires approximately four hours to chill the sump 40 degrees C. The thermometer located on the side of the ethylene glycol sump must be monitored to ensure the desired sump temperature is attained and maintained. Slight adjustments in the refrigeration unit thermostat can be expected due to the coarseness of its scale.

4. Energize the heater variacs by switching on the breakers in the breaker panel located in the laboratory space on the bulkhead next to the counter.

5. Set the heater variacs to the desired position, after ensuring that the switch panel for the heater tubes located on the apparatus has all switches in the "on" position. Monitor

apparatus pressure through the pressure gage at the top of the apparatus, ensuring system pressure does not exceed 30 psig.

6. Turn on the pump motors by pushing down on the arm of the appropriate breaker box for the pumps located on the bulkhead next to the ethylene glycol sump. The pumps are marked "auxiliary condenser" and "instrumented tube condenser," respectively. Flow in the auxiliary condensate system can be controlled with the individual gate valves located at the coil penetrations on the apparatus. The auxiliary condenser will produce the fastest adjustments to system pressure if pressure is rising too quickly. Flow through the instrumented tubes can be controlled by the ball valves located at the bottom of the respective flow meter.

7. Throttle down coolant flow to the supply pumps with the valve located before the pump suction. This will increase the pump life and reduce noise in the laboratory space.

B. SECURING PROCEDURES

1. Turn all variacs to the zero position and switch off all breakers in the power panel on the bulkhead.

2. Turn the breakers for the pumps to the off position at the switch boxes near the ethylene glycol sump.

3. If apparatus will not be operated for an extended period, turn the switch on the refrigeration control panel to the "off" position after passing through "on."

4. Allow the re-circulation pump to operate for at least ten minutes after switching off the refrigeration unit to

dissipate any back pressure in the system; then secure the pump.

APPENDIX C

DATA REDUCTION PROGRAM

```
1000 !  FILE:    DRP1F
1005 !  PURPOSE: This program collects and processes condensation data for
1010 !           the R-114 tube-bundle apparatus.
1015 !  CREATED: NOVEMBER 2, 1988
1020 !  UPDATED: November 8, 1988
1025 ! CHANGE HOD=3 AND USING CALCULATED CI FROM WILSON
1030    BEEP
1035    PRINTER IS 1
1040    PRINT USING "4X,""SELECT OPTION"""
1045    PRINT USING "6X,""0  TAKING DATA OR REPROCESING PREVIOUS DATA"""
1050    PRINT USING "6X,""1  PLOTTING H VS DELTA-T"""
1055    PRINT USING "6X,""2  PLOTTING HRAT VS N"""
1060    PRINT USING "6X,""3  PLOTTING WILSON"""
1065    PRINT USING "6X,""4  PURGE FILES"""
1070    PRINT USING "6X,""5  XYREAD"""
1075    PRINT USING "6X,""6  NUSSELT ESTIMATE"""
1080    PRINTER IS 701
1085    INPUT Icall
1090    IF Icall=0 THEN CALL Main
1095    IF Icall=1 THEN CALL Plot2
1100    IF Icall=2 THEN CALL Plot1
1105    IF Icall=3 THEN CALL Plot3
1110    IF Icall=4 THEN CALL Purge
1115    IF Icall=5 THEN CALL Xyread
1120    IF Icall=6 THEN CALL Nusselt
1125    END
1130    SUB Main
1135    COM /Cc/ C(7)
1140    COM /Fld/ Ift
1145    COM /Nus/ Iin,Tsat,Qdp1,Hnus
1150    COM /Will/ Doa(4),Dia(4),Kma(4),Iact
1155    COM /Wil2/ Delta,Isat,Nsets,Hod,Cia(3),Alpaa(3)
1160    DIM Fma(8,4),Fm(4),Emf(8),Tp(3),T(8),Ho(3),Qdp(3),Uo(3)
1165    DATA 33.4,20,34.4,34.5,23.5
1170    DATA 41.3,25,41.3,41.6,28.8
1175    DATA 49.1,30,48.4,48.6,34.1
1180    DATA 57.0,35,55.3,55.6,38.4
1185    DATA 64.8,40,62.3,62.7,44.6
1190    DATA 72.7,45,69.2,69.7,48.8
1195    DATA 80.6,50,76.3,76.7,55.2
1200    DATA 88.4,55,83.3,83.8,60.5
1205    DATA 96.3,60,90.2,90.8,65.6
1210    READ Fma(*)
1215    DATA 5.172,5.172,5.172,5.172
1220    READ Cia(*)
1225    DATA 0.10086091,25727.94369,-767345.8295,78025595.81
1230    DATA -9247486589,6.97688E11,-2.66192E13,3.94078E14
1235    READ C(*)
1240    DATA 0.015875,0.014000,0.0,0.0,0.0
```

```
1245  DATA 0.015259,0.010160,0.0,0.0,0.0
1250  DATA 386.0,42.975,0.0,0.0,0.0
1255  DATA 0.0005588,3
1260  READ Doa(*),Dia(*),Kma(*),Delta,Hod  ! Hod=H/Di
1265  L=1.2192  ! Condensing length
1270  Jset=0
1275  BEEP
1280  INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)",Dtg$
1285  OUTPUT 709;"TD";Dtg$
1290  BEEP
1295  INPUT "SELECT OPTION (0=DAQ, 1=FILE)",Im
1300  Ihard=1
1305  BEEP
1310  INPUT "WANT A HARDCOPY PRINTOUT (1=DEF=YES,0=NO)",Ihard
1315  BEEP
1320  INPUT "SELECT (0=R-114,1=STEAM,2=R-113,3=EG)",Ift
1325  Iin=1
1330  Isat=2
1335  BEEP
1340  INPUT "SELECT SAT TEMP MODE (0=LIQ,1=VAP,2=(LIQ+VAP)/2=DEF)",Isat
1345  IF Ihard=1 THEN PRINTER IS 701
1350  IF Im=0 THEN
1355     BEEP
1360     INPUT "GIVE A NAME FOR THE NEW DATA FILE",File$
1365     CREATE BDAT File$,20
1370     ASSIGN @File TO File$
1375     BEEP
1380     INPUT "ENTER TUBE CODE",Itube
1385     BEEP
1390     INPUT "ENTER EG CONCENTRATION (WT PERCENT)",Egrat
1395     ENTER 709;Dtg$
1400     OUTPUT @File;Dtg$
1405     OUTPUT @File;Itube,Egrat,Dd1,Dd2,Dd3,Dd4,Dd5
1410     Iact=10
1415     BEEP
1420     INPUT "SELECT (0=TOP,1=SECOND,....,10=BUNDLE=DEFAULT)",Iact
1425     PRINT
1430     PRINT USING "10X,""FILE NAME:     "",12A";File$
1435     PRINT
1440  ELSE
1445     BEEP
1450     INPUT "ENTER NAME OF EXISTING FILE",File$
1455     BEEP
1460     INPUT "ENTER NUMBER OF DATA SETS STORED",Nsets
1465     Iwil=1
1470     BEEP
1475     INPUT "WANT TO CALL WILSON? (1=DEFAULT=YES,0=NO)",Iwil
1480     IF Iwil=1 THEN
1485        BEEP
1490        INPUT "WHICH TUBE (0=TOP,1=SECOND,...,10=BUNDLE)",Iact
1495        CALL Wilson
1500        IF Ihard=1 THEN PRINTER IS 701
1505        PRINT
1510        PRINT USING "10X,""FILE NAME:     "",12A";File$
1515        PRINT
1520        IF Iact>9 THEN
1525           PRINT USING "10X,""INSIDE COEFFICIENTS:  "",4(DD.3D,2X)";Cia(*)
1530           PRINT USING "10X,""ALPHAS                    "",4(1X,MZ.3DE,2X)";Alp
```

```
aa(*)
1535           ELSE
1540             PRINT USING "10X,""INSIDE COEFFICIENT FOR TUBE "",D,"":  "",DD.3
D",Iact,Cia(Iact)
1545             PRINT USING "10X,""ALPHA FOR TUBE "",D,"":                       "",DD.3
D",Iact,Alpaa(Iact)
1550           END IF
1555         ELSE
1565           INPUT "ENTER CI VALUES (DEFAULT=5.172)",Cia(*)
1570         END IF
1575         ASSIGN @File TO File$
1580         ENTER @File;Dtg$
1585         ENTER @File;Itube,Egrat,Dd1,Dd2,Dd3,Dd4,Dd5
1586       INPUT "ENTER TUBE CODE",Itube
1590       END IF
1595       Iout=1
1600       BEEP
1605       INPUT "WANT TO CREATE AN OUTPUT FILE? (1=DEF=YES,0=NO)",Iout
1610       IF Iout=1 THEN
1615         BEEP
1620         INPUT "ENTER A NAME FOR OUTPUT FILE",Fout$
1625         CREATE BDAT Fout$,5
1630         ASSIGN @Fout TO Fout$
1635       END IF
1640 !
1645       Do=Doa(Itube)
1650       Di=Dia(Itube)
1655       Km=Kma(Itube)
1660       Ax=PI*Di^2/4    ! Cross-sectional area
1665       Ao=PI*Do*L
1670       Rm=Do*LOG(Do/Di)/(2*Km)
1675 !
1680       IF Im=0 THEN
1685         PRINTER IS 1
1690         BEEP
1695         PRINT "SET FLOWMETER READINGS CORRESPONDING TO:"
1700         PRINT "         ";Fma(Jset,1);"% OF METER 2 AND HIT CONTINUE"
1705         PAUSE
1710         PRINTER IS 701
1715         OUTPUT 709;"AR AF0 AL8 VRS"
1720         Nend=8      ! INCREASE TO 9 IF FIVE TUBES IN BUNDLE
1725         FOR I=0 TO Nend
1730           OUTPUT 709;"AS SA"
1735           Vsum=0
1740           FOR J=1 TO 5
1745             ENTER 709;E
1750             Vsum=Vsum+E
1755           NEXT J
1760           Emf(I)=Vsum/5
1765         NEXT I
1770         OUTPUT 709;"AR AF20 AL23 VRS"
1775         FOR I=0 TO 3
1780           OUTPUT 709;"AS SA"
1785           Vsum=0
1790           FOR J=1 TO 50
1795             ENTER 709;E
1800             Vsum=Vsum+E
1805 !           WAIT .25
1810           NEXT J
```

```
1815            Tp(I)=Vsum/50
1820         NEXT I
1825      ELSE
1830         ENTER @File.Fm(*),Emf(*),Tp(*)
1835      END IF
1840 !
1845 !    DATA ANALYSIS
1850 !
1855      Nend=8
1860      FOR I=0 TO Nend
1865         T(I)=FNTvsv(Emf(I))
1870      NEXT I
1875      Tvap=(T(0)+T(1)+T(2))/3
1880      Tliq=(T(3)+T(4))/2
1890         Tsat=Tliq
1895      END IF
1896      IF Isat=1 THEN
1900         Tsat=Tvap
1905      END IF
1906      IF Isat=2 THEN
1907         Tsat=(Tvap+Tliq)/2
1908      END IF
1910      FOR I=0 TO 4
1915         Fm(I)=Fma(Jset,I)
1920      NEXT I
1925      Jset=Jset+1
1930      PRINT
1935      PRINT USING "10X,""Data set number  = "",DD".Jset
1940      PRINT
1945      Ibeg=0
1950      Iend=3
1955      IF Iact<10 THEN
1960         Ibeg=Iact
1965         Iend=Iact
1970      END IF
1975      FOR I=Ibeg TO Iend
1980         Grad=FNGrad(Emf(I+5))
1985         Delt=ABS(Tp(I)/(Grad*10))
1990         Tavg=T(I+5)+Delt*.5
1995         Rhoeg=FNRhoeg(Tavg,Egrat)
2000         Nueg=FNNueg(Tavg,Egrat)
2005         Mueg=Nueg*Rhoeg
2010         Cpeg=FNCpeg(Tavg,Egrat)
2015         Keg=FNKeg(Tavg,Egrat)
2020         Preg=Cpeg*Mueg/Keg
2025         Mdot=FNFmcal(I,T(I+5),Fm(I))
2030         Veg=Mdot/(Rhoeg*Ax)
2035         Reeg=Veg*Di/Nueg
2040         Res=4*Mdot/(PI*Mueg*(Di-4*Delta))
2045         Qdot=Mdot*Cpeg*Delt
2050         Qdp(I)=Qdot/Ao
2055         IF I=0 OR I=Iact THEN
2060            Qdp1=Qdp(I)
2065            CALL Nusselt
2070         END IF
2075         Lmtd=Delt/LOG((Tsat-T(I+5))/(Tsat-T(I+5)-Delt))
2080         Uo(I)=Qdp(I)/Lmtd
2085         IF Reeg<4000 THEN
```

```
2090          Nueg=Cia(I)*(1+5.484E-3*Preg^.7*(Res/Hod)^1.25)^.5
2095       ELSE
2100          BEEP
2105          PRINT USING "10X,""INCORRECT TURBULENT CORRELATION"""
2110          Nueg=.027*Reeg^.8*Preg^.3333*Cfeg
2115       END IF
2120       Hi=Nueg*Keg/Di
2125       Ho(I)=1/(1/Uo(I)-Do/(Di*Hi)-Rm)
2130       IF I=0 OR I=Iact THEN
2135          PRINT USING "10X,""Mass flow rate              = "",MZ.3DE";Mdot
2136          PRINT USING "10X,""Inside Tube Dia. (m.)       = "",MZ.3DE";Dia(Itube
)
2137          PRINT USING "10X,""180 DEG OVER Dia. (HOD) = "",MZ.3DE";Hod
2140          PRINT USING "10X,""Inlet temperature           = "",MZ.3DE";T(I+5)
2145          PRINT USING "10X,""Saturation temp (Deg C) = "",MZ.3DE";Tsat
2146          PRINT USING "10X,""DELTA Tape Thickness        = "",MZ.3DE";Delta
2147          PRINT USING "10X,""DELT  temp  Dif.            = "",MZ.3DE";Delt
2148          PRINT USING "10X,""Log. Mean temp  Dif.        = "",MZ.3DE";Lmtd
2150          PRINT USING "10X,""Heat flux                   = "",MZ.3DE";Qdp(I)
2151          PRINT USING "10X,""Conductivity E.G.           = "",MZ.3DE";Keg
2152          PRINT USING "10X,""Conductivity Tube Metal = "",MZ.3DE";Km
2155          PRINT USING "10X,""Prandtl number              = "",MZ.3DE";Preg
2160          PRINT USING "10X,""Reynolds number             = "",MZ.3DE";Reeg
2161          PRINT USING "10X,""Reynolds number H&B S   = "",MZ.3DE";Res
2165          PRINT USING "10X,""Inside h.t.c.               = "",MZ.3DE";Hi
2166          PRINT USING "10X,""Inside NUSSULT NO.          = "",MZ.3DE";Nueg
2167          PRINT USING "10X,""OVERALL H.t.c. (Uo)         = "",MZ.3DE";Uo(I)
2170          PRINT
2175          PRINT USING "10X,""TUBE       FM      VEG       DELT       Uo
  HO           HNUS"""
2180          PRINT USING "10X,""  #       (%)     (m/s)      (K)             (W/m^2.
K)"""
2185          PRINT USING "10X,3D,4X,3D.DD,3X,Z.DD,4X,DD.3D,2X,MZ.3DE,3X,MZ.3DE
,3X,MZ.3DE,3X";I+1,Fm(I),Veg,Delt,Uo(I),Ho(I),Hnus
2190       ELSE
2195          PRINT USING "10X,3D,4X,3D.DD,3X,Z.DD,4X,DD.3D,2X,MZ.3DE,3X,MZ.3DE
,3X";I+1,Fm(I),Veg,Delt,Uo(I),Ho(I)
2200       END IF
2205    NEXT I
2210    IF Im=0 THEN
2215       Okaccpt=1
2220       BEEP
2225       INPUT "OK TO ACCEPT THIS SET (1=DEFAULT=YES, 0=NO)?",Okaccpt
2230       IF Okaccpt=1 THEN OUTPUT @File;Fm(*),Emf(*),Tp(*)
2235    END IF
2240    IF (Okaccpt=1 OR Im=1) AND Iout=1 THEN
2245       FOR I=0 TO 3
2250          OUTPUT @Fout;Ho(I),Qdp(I)
2255       NEXT I
2260    END IF
2265    IF Im=0 THEN
2270       Okrpt=1
2275       BEEP
2280       INPUT "WILL THERE BE ANOTHER RUN (1=YES=DEFAULT,0=NO)",Okrpt
2285       IF Okrpt=1 THEN 1680
2290    ELSE
2295       IF Jset<Nsets THEN 1680
2300    END IF
2305    ASSIGN @File TO *
```

```
2310    IF Iout=1 THEN ASSIGN @File TO *
2315    SUBEND
2320    DEF FNGrad(T)
2325    Grad=-3.877857E-5-2*4.7142857E-8*T
2330    RETURN Grad
2335    FNEND
2340    DEF FNKcu(T)
2345 !  OFHC COPPER 250 TO 300 K
2350    Tk=T+273.15
2355    K=434-.112*Tk
2360    RETURN K
2365    FNEND
2370    DEF FNNueg(Tc,Egr)
2375 !  RANGE OF VALIDITY:  -20 TO 20 DEG C
2380    Tk=Tc+273.15
2385    Nu1=7.1196507E-3-Tk*(7.4863347E-5-Tk*(2.6294943E-7-Tk*3.0833329E-10))
2390    Nu2=4.9237638E-3-Tk*(4.9213912E-5-Tk*(1.6437534E-7-Tk*1.8333331E-10))
2395    Nu3=8.6586293E-3-Tk*(8.8837902E-5-Tk*(3.0495032E-7-Tk*3.4999996E-10))
2400    A2=(Nu3-2*Nu2+Nu1)/200
2405    A1=(Nu2-Nu1-940*A2)/10
2410    A0=Nu1-42*A1-1764*A2
2415    Nu=A0+Egr*(A1+Egr*A2)
2420    RETURN Nu
2425    FNEND
2430    DEF FNCpeg(Tc,Egr)
2435 !  RANGE OF VALIDITY: 0 TO 20 DEG C
2440    Tk=Tc+273.15
2445    Cp1=1.6701550E+3+Tk*6.5
2450    Cp2=1.4748125E+3+Tk*6.25
2455    Cp3=9.5800500E+2+Tk*7.3
2460    A2=(Cp3-2*Cp2+Cp1)/200
2465    A1=(Cp2-Cp1-900*A2)/10
2470    A0=Cp1-40*A1-1600*A2
2475    Cp=A0+Egr*(A1+Egr*A2)
2480    RETURN Cp
2485    FNEND
2490    DEF FNRhoeg(T,Egr)
2495    Ro1=1.0607093E+3-T*(3.7031283E-1+T*4.0837183E-3)
2500    Ro2=1.0748272E+3-T*(4.4266195E-1+T*4.0939706E-3)
2505    Ro3=1.0885934E+3-T*(5.7355653E-1+T*6.1281405E-3)
2510    A2=(Ro3-2*Ro2+Ro1)/200
2515    A1=(Ro2-Ro1-900*A2)/10
2520    A0=Ro1-40*A1-1600*A2
2525    Ro=A0+Egr*(A1+Egr*A2)
2530    RETURN Ro
2535    FNEND
2540    DEF FNPreg(T,Egr)
2545    Pr=FNCpeg(T,Egr)*FNNueg(T,Egr)*FNRoeg(T,Egr)/FNKeg(T,Egr)
2550    RETURN Pr
2555    FNEND
2560    DEF FNKeg(Tc,Egr)
2565 !  RANGE OF VALIDITY:  -20 TO 20 DEG C
2570    Tk=Tc+273.15
2575    K1=2.2824708E-1+Tk*(5.5989286E-4+Tk*3.5714286E-7)
2580    K2=2.5846616E-1+Tk*(2.3978571E-4+Tk*7.1428571E-7)
2585    K3=3.2138932E-1-Tk*(3.0042857E-4-Tk*1.4285714E-6)
2590    A2=(K3-2*K2+K1)/200
2595    A1=(K2-K1-900*A2)/10
2600    A0=K1-40*A1-1600*A2
2605    K=A0+Egr*(A1+Egr*A2)
```

```
2610    RETURN K
2615    FNEND
2620    DEF FNTanh(x)
2625    P=EXP(x)
2630    Q=1/P
2635    Tanh=(P-Q)/(P+Q)
2640    RETURN Tanh
2645    FNEND
2650    DEF FNTvsv(V)
2655    COM /Cc/ C(7)
2660    T=C(0)
2665    FOR I=1 TO 7
2670          T=T+C(I)*V^I
2675    NEXT I
2680    RETURN T
2685    FNEND
2690    DEF FNBeta(T)
2695    Rop=FNRho(T+.1)
2700    Rom=FNRho(T-.1)
2705    Beta=-2/(Rop+Rom)*(Rop-Rom)/.2
2710    RETURN Beta
2715    FNEND
2720    DEF FNPsat(Tc)
2725  ! 0 TO 80 deg F CURVE FIT OF Psat
2730    Tf=1.8*Tc+32
2735    Pa=5.945525+Tf*(.15352082+Tf*(1.4840963E-3+Tf*9.6150671E-6))
2740    Pg=Pa-14.7
2745    IF Pg>0 THEN        ! +=PSIG,-=in Hg
2750       Psat=Pg
2755    ELSE
2760       Psat=Pg*29.92/14.7
2765    END IF
2770    RETURN Psat
2775    FNEND
2780    DEF FNFmcal(I,T,Fm)
2785    DIM B1(4),B2(4),B3(4),M1(4),M2(4),M3(4)
2790    DATA 3.48835E-3,6.71749E-3,-5.8103E-3,-5.5079E-3,4.125E-4
2795    DATA -1.47621E-2,2.53207E-3,-2.75396E-3,-4.30913E-3,-3.10937E-3
2796    DATA 1.048E-3,1.01292E-2,1.114E-2,-3.86717E-3,0.0
2800    DATA 1.71625E-3,2.70428E-3,1.93749E-3,1.92237E-3,2.56646E-3
2805    DATA 2.03462E-3,2.86716E-3,2.09517E-3,2.12433E-3,2.93127E-3
2806    DATA 1.7681E-3,2.70622E-3,2.00121E-3,2.2040E-3,0.0
2810    READ B1(*),B2(*),B3(*),M1(*),M2(*),M3(*)
2811    IF T<-7 THEN
2815       Z1=B1(I)+M1(I)*Fm
2820       Z2=B2(I)+M2(I)*Fm
2821       S=(Z2-Z1)/13
2822       C=Z1+S*20
2824    ELSE
2825       Z1=B2(I)+M2(I)*Fm
2826       Z2=B3(I)+M3(I)*Fm
2827       S=(Z2-Z1)/16
2828       C=Z1+S*7
2830    END IF
2835    Mdot=C+S*T
2840    RETURN Mdot
2845    FNEND
2850    SUB Xyread
2855    BEEP
```

```
2860     INPUT "ENTER FILE NAME",File$
2865     BEEP
2870     INPUT "ENTER NUMBER OF X,Y PAIRS",N
2875     ASSIGN @File TO File$
2880     FOR I=1 TO N
2885         ENTER @File,X,Y
2890         PRINT X,Y
2895     NEXT I
2900     SUBEND
2905     SUB Purge
2910     BEEP
2915     INPUT "ENTER FILE NAME TO BE DELETED",File$
2920     PURGE File$
2925     GOTO 2910
2930     SUBEND
2935     SUB Wilson
2940     COM /Wil1/ Doa(4),Dia(4),Kma(4),Iact
2945     COM /Wil2/ Delta,Isat,Nsets,Hod,Cia(3),Alpaa(3)
2950     DIM Fm(4),Emf(8),Tp(3),T(8),Xa(20),Ya(20)
2955     BEEP
2960     INPUT "PLEASE RE-ENTER NAME OF FILE",File$
2965     ASSIGN @File TO File$
2970     INPUT "ENTER TUBE CODE",Itube
2975     BEEP
2980     INPUT "GIVE A NAME FOR XY FILE",Xy$
2985     CREATE BDAT Xy$,5
2990     ASSIGN @Xy TO Xy$
2995     L=1.2192
3000     Do=Doa(Itube)
3005     Di=Dia(Itube)
3010     Km=Kma(Itube)
3015     Ax=PI*Di^2/4   ! Cross-sectional area
3020     Ao=PI*Do*L
3025     Rm=Do*LOG(Do/Di)/(2*Km)
3030 !
3035 !   Initial values
3040     Tf=Tsat
3045     Alpa=.655
3050     Ci=5.172
3055     G=9.81
3060     Ibeg=0
3065     Iend=3   !CHANGE TO 4. IF FIVE TUBES IN BUNDLE
3070     IF Iact<10 THEN
3075        Ibeg=Iact
3080        Iend=Iact
3085     END IF
3090 !
3095     FOR I=Ibeg TO Iend
3100         Sx=0
3105         Sy=0
3110         Sxs=0
3115         Sxy=0
3120         Jset=0
3125         ASSIGN @File TO File$
3130         ENTER @File;Dtg$,Itube,Egrat,Dd1,Dd2,Dd3,Dd4,Dd5
3135         ENTER @File;Fm(*),Emf(*),Tp(*)
3140         FOR J=0 TO 8
3145             T(J)=FNTvsv(Emf(J))
3150         NEXT J
3155         Tvap=(T(0)+T(1)+T(2))/3
```

```
3160         Tliq=(T(3)+T(4))/2
3165         IF Isat=0 THEN
3170            Tsat=Tliq
3175         ELSE
3180            Tsat=Tvap
3185         END IF
3190         Grad=FNGrad(T(I+5))
3195         Delt=ABS(Tp(I)/(Grad*10))
3200         Tavg=T(I+5)+Delt*.5
3205 !
3210 !       Water/Ethyiene Glycol Mixture Properties
3215         Rhoeg=FNRhoeg(Tavg,Egrat)
3220         Nueg=FNNueg(Tavg,Egrat)
3225         Mueg=Nueg*Rhoeg
3230         Cpeg=FNCpeg(Tavg,Egrat)
3235         Keg=FNKeg(Tavg,Egrat)
3240         Preg=Cpeg*Mueg/Keg
3245 !
3250         Mdot=FNFmcal(I,T(I+5),Fm(I))
3255         Veg=Mdot/(Rhoeg*Ax)
3260         Reeg=Veg*Di/Nueg
3265         Res=4*Mdot/(PI*Mueg*(Di-4*Delta))
3270         Qdot=Mdot*Cpeg*Delt
3275         Qdp=Qdot/Ao
3280         Lmtd=Delt/LOG((Tsat-T(I+5))/(Tsat-T(I+5)-Delt))
3285         Uo=Qdp/Lmtd
3290         Omega=(1+5.484E-3*Preg^.7*(Res/Hod)^1.25)^.5
3295 !
3300 !       R-114 Properties
3305         Hfg=FNHfg(Tsat)
3310         Kf=FNK(Tf)
3315         Rhof=FNRho(Tf)
3320         Muf=FNMu(Tf)
3325 !
3330         F=(Kf^3*Rhof^2*G*Hfg/(Muf*Do*Qdp))^.33333
3335         Ho=Alpa*F
3340         Two=Tsat-Qdp/Ho
3345         Tf=Tsat/3+2*Two/3
3350         Y=(1/Uo-Rm)*F
3355         X=Do*F/(Keg*Omega)
3360         PRINT "OMEGA=",Omega;"F=";F;"X=";X;"Y=";Y
3365         Xa(Jset)=X    !   INEFFICIENT (MODIFY LATER)
3370         Ya(Jset)=Y
3375         Sx=Sx+X
3380         Sy=Sy+Y
3385         Sxs=Sxs+X*X
3395         Jset=Jset+1
3400         IF Jset<Nsets THEN 3135
3405         ASSIGN @File TO *
3410         Slope=(Nsets*Sxy-Sx*Sy)/(Nsets*Sxs-Sx^2)
3415         Intcpt=(Sy-Slope*Sx)/Nsets
3420         Cic=1/Slope
3425         Alpac=1/Intcpt
3430         Cerr=ABS((Ci-Cic)/Cic)
3435         Aerr=ABS((Alpac-Alpa)/Alpac)
3440         IF Cerr>.001 OR Aerr>.001 THEN
3445            Alpa=(Alpa+Alpac)*.5
3450            Ci=(Ci+Cic)*.5
3455            PRINT "CIC=",Cic;"ALPA=",Alpa
```

```
3460          GOTO 3100
3465       END IF
3470       BEEP
3475       BEEP
3480       PRINTER IS 1
3485       PRINT "CIC=";Cic;"ALFA=";Alpa
3490       Cia(I)=Cic
3495       Alpaa(I)=Alpac
3500       PRINTER IS 701
3505       FOR J=0 TO Nsets-1
3510           OUTPUT @Xy;Xa(J),Ya(J)
3515       NEXT J
3520       PRINTER IS 1
3525    NEXT I
3530    ASSIGN @Xy TO *
3535    SUBEND
3540    SUB Nusseit
3545    COM /Nus/ Iin,Tsat,Qdp,Hoc
3550    Do=.0159
3555    Ho=1000
3560    IF Iin=0 THEN
3565       BEEP
3570       INPUT "ENTER TSAT AND HEAT FLUX",Tsat,Qdp
3575    END IF
3580    Hfg=FNHfg(Tsat)
3585    Two=Tsat-Qdp/Ho
3590    Tf=Tsat/3+2*Two/3
3595    Kf=FNK(Tf)
3600    Rhof=FNRho(Tf)
3605    Muf=FNMu(Tf)
3610    Hoc=.655*(Kf^3*Rhof^2*9.81*Hfg/(Muf*Do*Qdp))^.333333
3615    IF ABS((Ho-Hoc)/Hoc)>.001 THEN
3620       Ho=(Ho+Hoc)*.5
3625       GOTO 3585
3630    END IF
3635    IF Iin=0 THEN PRINT "HO=";Hoc
3640    SUBEND
3645    SUB Plot1
3650    DIM Yaa(4)
3655    PRINTER IS 705
3660    Idv=1
3665    BEEP
3670    INPUT "OK TO USE DEFAULT VALUES (1=DEF=Y,0=N)",Idv
3675    IF Idv=1 THEN
3680       Itn=2
3685       Xmin=1
3690       Xmax=5
3695       Xstep=1
3700       Ymin=0
3705       Ymax=2.0
3710       Ystep=.5
3715    ELSE
3725       INPUT "ENTER MINIMUM AND MAXIMUM X-VALUES",Xmin,Xmax
3730       BEEP
3735       INPUT "ENTER MINIMUM AND MAXIMUM Y-VALUES",Ymin,Ymax
3740       BEEP
3745       INPUT "ENTER STEP SIZE FOR X-AXIS",Xstep
3750       BEEP
3755       INPUT "ENTER STEP SIZE FOR Y-AXIS",Ystep
```

```
3760    END IF
3765    PRINT "IN;SP1;IP 2300,1800,8300,5600;"
3770    PRINT "SC 0,100,0,100;TL 2,0;"
3775    Sfx=100/(Xmax-Xmin)
3780    Sfy=100/(Ymax-Ymin)
3785    PRINT "PU 0,0 PD"
3790    FOR Xa=Xmin TO Xmax STEP Xstep
3795        X=(Xa-Xmin)*Sfx
3800        PRINT "PA";X;",0; XT;"
3805    NEXT Xa
3810    PRINT "PA 100,0;PU;"
3815    PRINT "PU PA 0,0 PD"
3820    FOR Ya=Ymin TO Ymax STEP Ystep
3825        Y=(Ya-Ymin)*Sfy
3830        PRINT "PA 0,";Y;"YT"
3835    NEXT Ya
3840    PRINT "PA 0,100 TL 0 2"
3845    FOR Xa=Xmin TO Xmax STEP Xstep
3850        X=(Xa-Xmin)*Sfx
3855        PRINT "PA";X;",100; XT"
3860    NEXT Xa
3865    PRINT "PA 100,100 PU PA 100,0 PD"
3870    FOR Ya=Ymin TO Ymax STEP Ystep
3875        Y=(Ya-Ymin)*Sfy
3880        PRINT "PD PA 100,";Y;"YT"
3885    NEXT Ya
3890    PRINT "PA 100,100 PU"
3895    PRINT "PA 0,-2 SR 1.5,2"
3900    FOR Xa=Xmin TO Xmax STEP Xstep
3905        X=(Xa-Xmin)*Sfx
3910        PRINT "PA";X;",0;"
3915        PRINT "CP -2,-1;LB";Xa;""
3920    NEXT Xa
3925    PRINT "PU PA 0,0"
3930    FOR Ya=Ymin TO Ymax STEP Ystep
3935        Y=(Ya-Ymin)*Sfy
3940        PRINT "PA 0,";Y;""
3945        PRINT "CP -4,-.25;LB";Ya;""
3950    NEXT Ya
3955    BEEP
3960    INPUT "SELECT MODE (0=HN/H1,1=HN(avg)/H1)",Ism
3965    Ism=Ism+1
3970    IF Idv=1 THEN
3975       IF Ism=1 THEN Ylabel$="HN/H1"
3980       IF Ism=2 THEN Ylabel$="HN(avg)/H1"
3985       Xlabel$="Tube Number"
3990    ELSE
3995       BEEP
4000       INPUT "ENTER X-LABEL",Xlabel$
4005       BEEP
4010       INPUT "ENTER Y-LABEL",Ylabel$
4015    END IF
4020    PRINT "SR 1.5,2;PU PA 50,-10 CP";-LEN(Xlabel$)/2;"0;LB";Xlabel$;""
4025    PRINT "PA -11,50 CP 0,";-LEN(Ylabel$)/2*5/6;"DI 0,1;LB";Ylabel$;""
4030    PRINT "CP 0,0 DI"
4035    Okp=1
4040    BEEP
4045    INPUT "WANT TO PLOT DATA FROM A FILE (1=DEF=Y,0=N)?",Okp
```

```
4055        BEEP
4060        INPUT "ENTER THE NAME OF THE DATA FILE",Dfile$
4065        ASSIGN @File TO Dfile$
4070        BEEP
4075        INPUT "ENTER THE BEGINNING RUN NUMBER",Md
4080        BEEP
4085        INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED",Nsets
4090        BEEP
4095        INPUT "SELECT A SYMBOL FOR THE PLOTTER (1=*,2=+,3=c,4=o,5=^)",Sy
4100        PRINT "PU DI"
4105        IF Sy=1 THEN PRINT "SM*"
4110        IF Sy=2 THEN PRINT "SM+"
4115        IF Sy=3 THEN PRINT "SMc"
4120        IF Sy=4 THEN PRINT "SMo"
4125        IF Sy=5 THEN PRINT "SM^"
4130        FOR I=1 TO Nsets
4135            FOR J=0 TO 3
4140                ENTER @File;Yaa(J),D
4145                IF J=0 THEN Ytop=Yaa(0)
4150                Yaa(J)=Yaa(J)/Ytop
4155            NEXT J
4160            FOR J=0 TO 3
4165                X=(J+1-Xmin)*Sfx
4170                Y=(Yaa(J)-Ymin)*Sfy
4175                PRINT "PA",X,Y,""
4180            NEXT J
4185        NEXT I
4190        BEEP
4195        ASSIGN @File TO *
4200        GOTO 4040
4205    END IF
4210    BEEP
4215    INPUT "LIKE TO PLOT THE NUSSELT RELATION (1=Y,0=N)?",Oknus
4220    PRINT "PU;SM"
4225    IF Oknus=1 THEN
4230        FOR Xa=Xmin TO Xmax STEP Xstep/50
4235            X=(Xa-Xmin)*Sfx
4240            IF Ism=1 AND Xa>Xmin THEN Ya=Xa^.75-(Xa-1)^.75
4245            IF Ism=2 AND Xa>Xmin THEN Ya=Xa^(-.25)
4250            IF Xa=Xmin THEN Ya=1
4255            Y=(Ya-Ymin)*Sfy
4260            PRINT "PA",X,Y,"PD"
4265        NEXT Xa
4270        BEEP
4275        PRINT "PU"
4280        INPUT "MOVE THE PEN TO LABEL THE NUSSELT LINE",Ok
4285        PRINT "LBNusselt"
4290    END IF
4295    IF Ism=2 THEN
4300        BEEP
4305        INPUT "LIKE TO PLOT EXPTL CURVE (1=Y,0=N)",Okex
4310        Nq=0
4315        IF Okex=1 THEN
4320            BEEP
4325            INPUT "ENTER THE EXPONENT",Ex
4330            FOR Xa=Xmin TO Xmax STEP Xstep/10
4335                Nq=Nq+1
4340                Ya=Xa^(-Ex)
4345                X=(Xa-Xmin)*Sfx
4350                Y=(Ya-Ymin)*Sfy
```

```
4355                IF Nq MOD 2=0 THEN
4360                   PRINT "PA",X,Y,"PD"
4365                ELSE
4370                   PRINT "PA",X,Y,"PU"
4375                END IF
4380             NEXT Xa
4385             PRINT "PU"
4390             BEEP
4395             INPUT "MOVE PEN TO LABEL AND HIT ENTER",Ok
4400             PRINT "LBs=2"
4405             PRINT "PR -1 0"
4410             PRINT "LB",Ex,""
4415             GOTO 4300
4420          END IF
4425       END IF
4430       GOTO 4510
4435       BEEP
4440       INPUT "LIKE TO PLOT KERN RELATIONSHIP (1=Y,0=N)?",Yes
4445       IF Yes=1 THEN
4450          FOR Xa=Xmin TO Xmax STEP Xstep/20
4455               Ya=Xa^(-1/6)
4460               X=(Xa-Xmin)*Sfx
4465               Y=(Ya-Ymin)*Sfy
4470               PRINT "PA",X,Y,"PD"
4475          NEXT Xa
4480          PRINT "PU"
4485          BEEP
4490          INPUT "MOVE THE PEN TO LABEL KERN RELATIONSHIP",Ok
4495          PRINT "LBkern:PU"
4500       END IF
4505       PRINT "PU PA 0,0"
4510       BEEP
4515       INPUT "LIKE TO PLOT EISSENBERG RELATION (1=Y,0=N)?",Okei
4520       IF Okei=1 THEN
4525          FOR Xa=Xmin TO Xmax STEP Xstep/10
4530               Ya=.5+.42*Xa^(-.25)
4535               X=(Xa-Xmin)*Sfx
4540               Y=(Ya-Ymin)*Sfy
4545               PRINT "PA",X,Y,"PD"
4550          NEXT Xa
4555          PRINT "PU"
4560          BEEP
4565          INPUT "MOVE THE PEN TO LABEL THE EISSENBERG LINE",Ok
4570          PRINT "LBEissenberg:PU"
4575       END IF
4580       PRINT "PU SP0"
4585       SUBEND
4590       DEF FNPvst(Tc)
4595       COM /Fld/ Ift
4600       DIM K(8)
4605       IF Ift=0 THEN
4610          BEEP
4615          PRINT "PVST CORRELATION NOT AVAILABLE FOR R-114"
4620          STOP
4625       END IF
4630       IF Ift=1 THEN
4635          DATA -7.691234564,-26.08023696,-168.1706546,64.23285504,-118.9646225
4640          DATA 4.16711732,20.9750676,1.E9,6
4645          READ K(*)
```

```
4650       T=(Tc+273.15)/647.3
4655       Sum=0
4660       FOR N=0 TO 4
4665          Sum=Sum+K(N)*(1-T)^(N+1)
4670       NEXT N
4675       Br=Sum/(T*(1+K(5)*(1-T)+K(6)*(1-T)^2))-(1-T)/(K(7)*(1-T)^2+K(8))
4680       Pr=EXP(Br)
4685       P=22120000*Pr
4690    END IF
4695    IF Ift=2 THEN
4700       Tf=Tc*1.8+32+459.6
4705       P=10^(33.0655-4330.98/Tf-9.2635*LGT(Tf)+2.0539E-3*Tf)
4715    END IF
4720    IF Ift=3 THEN
4725       A=9.394685-3066.1/(Tc+273.15)
4730       P=133.32*10^A
4735    END IF
4740    RETURN P
4745    FNEND
4750    DEF FNHfg(T)
4755    COM /Fld/ Ift
4760    IF Ift=0 THEN
4765       Tf=T*1.8+32
4770       Hfg=6.1451558E+1-Tf*(6.951079E-2+Tf*(1.3988688E-4+1.9607843E-7*Tf))
4775       Hfg=Hfg*2326
4780    END IF
4785    IF Ift=1 THEN
4790       Hfg=2477200-2450*(T-10)
4795    END IF
4800    IF Ift=2 THEN
4805       Tf=T*1.8+32
4810       Hfg=7.0557857E+1-Tf*(4.838052E-2+1.2619048E-4*Tf)
4815       Hfg=Hfg*2326
4820    END IF
4825    IF Ift=3 THEN
4830       Tk=T+273.15
4835       Hfg=1.35264E+6-Tk*(6.38263E+2+Tk*.747462)
4840    END IF
4845    RETURN Hfg
4850    FNEND
4855    DEF FNMu(T)
4860    COM /Fld/ Ift
4865    IF Ift=0 THEN
4870       Tk=T+273.15
4875       Mu=EXP(-4.4636+1011.47/Tk)*1.E-3
4880    END IF
4885    IF Ift=1 THEN
4890       A=247.8/(T+133.15)
4895       Mu=2.4E-5*10^A
4900    END IF
4905    IF Ift=2 THEN
4910       Mu=8.9629819E-4-T*(1.1094609E-5-T*5.566829E-8)
4915    END IF
4920    IF Ift=3 THEN
4925       Tk=1/(T+273.15)
4930       Mu=EXP(-11.0179+Tk*(1.744E+3-Tk*(2.80335E+5-Tk*1.12661E+8)))
4935    END IF
4940    RETURN Mu
4945    FNEND
```

```
4950    DEF FNVvst(Tt)
4955    COM /Fld/ Ift
4960    IF Ift=0 THEN
4965       BEEP
4970       PRINT "VVST CORRELATION NOT AVAILABLE FOR R-114"
4975       STOP
4980    END IF
4985    IF Ift=1 THEN
4990       P=FNPvst(Tt)
4995       T=Tt+273.15
5000       X=1500/T
5005       F1=1/(1+T*1.E-4)
5010       F2=(1-EXP(-X))^2.5*EXP(X)/X^.5
5015       B=.0015*F1-.000942*F2-.0004882*X
5020       K=2*P/(461.52*T)
5025       V=(1+(1+2*B*K)^.5)/K
5030    END IF
5035    IF Ift=2 THEN
5040       Tf=Tt*1.8+32
5045       V=13.955357-Tf*(.16127262-Tf*5.1726190E-4)
5050       V=V/16.018
5055    END IF
5060    IF Ift=3 THEN
5065       Tk=Tt+273.15
5070       P=FNPvst(Tt)
5075       V=133.95*Tk/P
5080    END IF
5085    RETURN V
5090    FNEND
5095    DEF FNCp(T)
5100    COM /Fld/ Ift
5105    IF Ift=0 THEN
5110       Tk=T+273.15
5115       Cp=.40118+Tk*(1.65007E-3+Tk*(1.51494E-6-Tk*6.67853E-10))
5120    END IF
5125    IF Ift=1 THEN
5130       Cp=4.21120858-T*(2.26826E-3-T*(4.42361E-5+2.71428E-7*T))
5135    END IF
5140    IF Ift=2 THEN
5145       Cp=9.2507273E-1+T*(9.3400433E-4+1.7207792E-6*T)
5150    END IF
5155    IF Ift=3 THEN
5160       Tk=T+273.15
5165       Cp=4.1868*(1.6884E-2+Tk*(3.35083E-3-Tk*(7.224E-6-Tk*7.61748E-9)))
5170    END IF
5175    RETURN Cp*1000
5180    FNEND
5185    DEF FNRho(T)
5190    COM /Fld/ Ift
5195    IF Ift=0 THEN
5200       Tk=T+273.15
5205       X=1-(1.8*Tk/753.95)
5210       Ro=36.32+61.146414*X^(1/3)+16.418015*X+17.476838*X^.5+1.119828*X^2
5215       Ro=Ro/.062428
5220    END IF
5225    IF Ift=1 THEN
5230       Ro=999.52946+T*(.01269-T*(5.482513E-3-T*1.234147E-5))
5235    END IF
5240    IF Ift=2 THEN
```

```
5245       Ro=1.6207479E+3-T*(2.2186346+T*2.3576291E-3)
5250    END IF
5255    IF Ift=3 THEN
5260       Tk=T+273.15-338.15
5265       Vf=9.24848E-4+Tk*(6.2796E-7+Tk*(9.2444E-10+Tk*3.057E-12))
5270       Ro=1/Vf
5275    END IF
5280    RETURN Ro
5285    FNEND
5290    DEF FNPr(T)
5295    Pr=FNCp(T)*FNMu(T)/FNK(T)
5300    RETURN Pr
5305    FNEND
5310    DEF FNK(T)
5315    COM /Fld/ Ift
5320    IF Ift=0 THEN K=.071-.000261*T
5325    IF Ift=1 THEN
5330       X=(T+273.15)/273.15
5335       K=-.92247+X*(2.8395-X*(1.8007-X*(.52577-.07344*X)))
5340    END IF
5345    IF Ift=2 THEN
5350       K=8.2095238E-2-T*(2.2214286E-4+T*2.3809524E-8)
5355    END IF
5360    IF Ift=3 THEN
5365       Tk=T+273.15
5375    END IF
5380    RETURN K
5385    FNEND
5390    DEF FNHf(T)
5395    COM /Fld/ Ift
5400    IF Ift=0 THEN
5405       BEEP
5410       PRINT "HF CORRELATION NOT FOR R-114"
5415       STOP
5420    END IF
5425    IF Ift=1 THEN
5430       Hf=T*(4.203849-T*(5.88132E-4-T*4.55160317E-6))
5435    END IF
5440    IF Ift=2 THEN
5445       Tf=T*1.8+32
5450       Hf=8.2078571+Tf*(.19467857+Tf*1.3214286E-4)
5455       Hf=Hf*2.326
5460    END IF
5465    IF Ift=3 THEN
5470       Hf=250   ! TO BE VERIFIED
5475    END IF
5480    RETURN Hf*1000
5485    FNEND
5490    SUB Plot2
5495    COM /Drl/ Star,Sym,Icon
5500    COM /Fld/ Ift
5505    DIM C(9),Xya(7),Doa(3)
5510    DATA 0.0158,0.0158,0.0158,0.0158
5515    READ Doa(*)
5520    Fw=1
5525    PRINTER IS 1
5530    BEEP
5535    PRINT USING "4X,""Select Option X-Y Limits:"""
5540    PRINT USING "6X,""0 Use default values"""
```

```
5545   PRINT USING "6X,""1 Use new values"""
5550   INPUT Ord
5555   BEEP
5560   INPUT "ENTER TUBE CODE",Icode
5565   Do=Dca(Itube)
5570   Iht=2
5575   BEEP
5580   PRINT USING "4X,""Select option """
5585   PRINT USING "6X,""0 h versus q"""
5590   PRINT USING "6X,""1 q versus Delta-T"""
5595   PRINT USING "6X,""2 h versus Delta-T (default)"""
5600   INPUT Iht
5605   PRINTER IS 705
5610   IF Okd=0 THEN !AXIS DEFAULT VALUES
5615      IF Iht=0 THEN !(h vs q)
5620         Ymin=0
5625         Ymax=60
5630         Ystep=10
5635         Xmin=.2
5640         Xmax=1.4
5645         Xstep=.2
5650      END IF
5655      IF Iht=1 THEN !(q vs t)
5660         Xmin=0
5665         Ymin=0
5670         Ymax=.5
5675         Xmax=15
5680         Xstep=3
5685         Ystep=.1
5690      END IF
5695      IF Iht=2 THEN !(h vs t)
5700         Xmin=0
5705         Ymin=0
5710         Xmax=50
5715         Ymax=6
5720         Xstep=10
5725         Ystep=1
5730      END IF
5735   END IF
5740   IF Okd=1 THEN
5745      BEEP
5750      INPUT "ENTER MINIMUM AND MAXIMUM X-VALUES",Xmin,Xmax
5755      BEEP
5760      INPUT "ENTER MINIMUM AND MAXIMUM Y-VALUES",Ymin,Ymax
5765      BEEP
5770      INPUT "ENTER STEP SIZE FOR X-AXIS",Xstep
5775      BEEP
5780      INPUT "ENTER STEP SIZE FOR Y-AXIS",Ystep
5785   END IF
5790   BEEP
5795   PRINT "IN;SP1;IP 2300,1800,8300,6800;"
5800   PRINT "SC 0,100,0,100;TL 2,0;"
5805   Sfx=100/(Xmax-Xmin)
5810   Sfy=100/(Ymax-Ymin)
5815   BEEP
5820   Icg=0
5825   INPUT "LIKE TO BY-PASS CAGE (1=Y,0=N=DEFAULT)?",Icg
5830   IF Icg=1 THEN 6175
5835   PRINT "PU 0,0 PD"
5840   FOR Xa=Xmin TO Xmax STEP Xstep
```

```
5845        X=(Xa-Xmin)*Sfx
5850        PRINT "PA";X,",0; XT;"
5855    NEXT Xa
5860    PRINT "PA 100,0;PU;"
5865    PRINT "PU PA 0,0 PD"
5870    FOR Ya=Ymin TO Ymax STEP Ystep
5875        Y=(Ya-Ymin)*Sfy
5880        PRINT "PA 0,",Y,"YT"
5885    NEXT Ya
5890    PRINT "PA 0,100 TL 0 2"
5895    FOR Xa=Xmin TO Xmax STEP Xstep
5900        X=(Xa-Xmin)*Sfx
5905        PRINT "PA";X,",100; XT"
5910    NEXT Xa
5915    PRINT "PA 100,100 PU PA 100,0 PD"
5920    FOR Ya=Ymin TO Ymax STEP Ystep
5925        Y=(Ya-Ymin)*Sfy
5930        PRINT "PD PA 100,",Y,"YT"
5935    NEXT Ya
5940    PRINT "PA 100,100 PU"
5945    PRINT "PA 0,-2 SR 1.5,2"
5950    FOR Xa=Xmin TO Xmax STEP Xstep
5955        X=(Xa-Xmin)*Sfx
5960        PRINT "PA";X,",0;"
5965        IF Xa<1 AND Xa<>0 THEN PRINT "CP -1.5,-1;LB0;PR -1,0;LB";Xa;""
5970        IF Xa=0 THEN PRINT "CP -.5,-1;LB0"
5975        Xin=0
5980        IF Xa MOD 1=0 THEN Xin=1
5985        IF Xa>=10 THEN PRINT "CP -2,-1;LB";Xa;""
5990        IF Xa>1 AND Xa<10 AND Xin=1 THEN PRINT "CP -1.25,-1;LB";Xa;""
5995        IF Xa>1 AND Xin=0 THEN PRINT "CP -2,-1;LB";Xa;""
6000        IF Xa=1 THEN PRINT "CP -1,-1;LB1.0"
6005    NEXT Xa
6010    PRINT "PU PA 0,0"
6015    FOR Ya=Ymin TO Ymax STEP Ystep
6020        Y=(Ya-Ymin)*Sfy
6025        PRINT "PA 0,";Y,""
6035        IF Ya<1 AND Ya<>0 THEN PRINT "CP -4,-.25;LB0;PR -2,0;LB",Ya;""
6040        IF Ya=0 THEN PRINT "CP -2,-.25,LB0"
6045        IF Ya>1 AND Iht<2 THEN PRINT "CP -5,-.25;LB";Ya;""
6050        IF Ya>9 AND Iht=2 THEN PRINT "CP -4,-.25;LB";Ya;""
6055        IF Ya>0 AND Ya<10 AND Iht=2 THEN PRINT "CP -3,-.25,LB",Ya;""
6060        IF Ya=1 THEN PRINT "CP -4,-.25;LB1.0"
6065    NEXT Ya
6070    IF Okd=1 THEN
6075       BEEP
6080       INPUT "ENTER X-LABEL",Xlabel$
6085       BEEP
6090       INPUT "ENTER Y-LABEL",Ylabel$
6095    END IF
6100    IF Iht<>1 THEN
6105       PRINT "SR 1.5,2;PU PA -12,35;DI 0,1;LBh;PR 1,0.5;LBo;PR -1,0.5;LB/(
kW/m"
6110       PRINT "PR -1,0.5;SR 1,1.5;LB2;SR 1.5,2;PR .5,.5;LB.;PR .5,0;LBK)"
6115    ELSE
6120       PRINT "PA -12,39;DI 0,1;LBq/(MW/m;SR 1,1.5;PR -1,0.5,LB2;SR 1.5,2.P
R 1.0,0.5;LB)"
6125    END IF
6130    IF Iht=0 THEN
```

```
6135      PRINT "SR 1.5,2;PU PA 40,-10;DI;LBq/(MW/m;PR 0.5,1;SR 1,1.5;LB2;SR
1.5,2;PR .5,-1;LB)"
6140    ELSE
6145      PRINT "DI PA 38,-10;LB(T;PR .5,-1;LBs;PR .5,1;LB-T;PR -2.4,3 PD PR
 2,0 PU;PR .5,-4;"
6150      PRINT "LBwo;PR .5,1;LB)/K"
6155    END IF
6160    PRINT "CP 0,0 DI"
6165    Xlg=1.E+6
6170    Xug=-1.E+6
6175    Xal=50
6180    Yal=95
6185    Nrun=0
6190    BEEP
6195    INPUT "WANT TO PLOT DATA FROM A FILE (1=Y,0=N)?",Ok
6200    Xll=1.E+6
6205    Xul=-1.E+6
6210    Okp=0
6215    IF Ok=1 THEN
6220      BEEP
6225      INPUT "ENTER THE NAME OF THE PLOT DATA FILE",D_file$
6230      ASSIGN @File TO D_file$
6235      IF Icomb<>0 THEN 6265
6240      Sx=0
6245      Sy=0
6250      Sx2=0
6255      Sxy=0
6260      Md=1
6265      BEEP
6270      INPUT "ENTER THE BEGINNING RUN NUMBER (DEF=1)",Md
6275      Npairs=9
6280      BEEP
6285      INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED (DEF=9)",Npairs
6290      Nrun=Nrun+Npairs
6295      PRINTER IS 1
6300      BEEP
6305      PRINT USING "4X,""Select a symbol:"""
6310      PRINT USING "4X,"" 1  Star     2  Plus sign"""
6315      PRINT USING "4X,"" 3  Circle   4  Square"""
6320      PRINT USING "4X,"" 5  Rombus"""
6325      PRINT USING "4X,"" 6  Right-side-up triangle"""
6330      PRINT USING "4X,"" 7  Up-side-down triangle"""
6335      INPUT Sym
6340      BEEP
6345      INPUT "ENTER TUBE NUMBER FOR PLOTTING (0=TOP,1=SECOND....)",Itube
6350      PRINTER IS 705
6355      IF Sym=1 THEN PRINT "SM*"
6360      IF Sym=2 THEN PRINT "SM+"
6365      IF Sym=3 THEN PRINT "SMo"
6370      IF Md>1 THEN
6375        FOR I=1 TO (Md-1)
6380            ENTER @File;Xya(*)
6385        NEXT I
6390      END IF
6395      FOR I=1 TO Npairs
6400          ENTER @File;Xya(*)
6405          Ya=Xya(Itube*2)
6410          Xa=Xya(Itube*2+1)
6415          Yc=LOG(Xa)
```

```
6420       Xc=LOG(Xa/Ya)
6425       Sx=Sx+Xc
6430       Sy=Sy+Yc
6435       Sx2=Sx2+Xc^2
6440       Sxy=Sxy+Xc*Yc
6445       IF Int=Ø THEN
6450          Xt=Ya
6455          Ya=Ya/Xa
6460          Xa=Xt
6465          IF Xa/1.E+6>Xul THEN Xul=Xa/1.E+6
6470          IF Xa/1.E+6<Xll THEN Xll=Xa/1.E+6
6475       END IF
6480       IF Int=Ø THEN
6485          X=(Xa*1.E-6-Xmin)*Sfx
6490          Y=(Ya*1.E-3-Ymin)*Sfy
6495       END IF
6500       IF Int=1 THEN
6505          X=(Xa-Xmin)*Sfx
6510          Y=(Ya*1.E-6-Ymin)*Sfy
6515       END IF
6520       IF Int=2 THEN
6525          X=(Xa/Ya-Xmin)*Sfx
6530          Y=(Ya*1.E-3-Ymin)*Sfy
6535       END IF
6540       IF Y>1ØØ OR Y<Ø THEN 6585
6545       IF Sym>3 THEN PRINT "SM"
6550       IF Sym<4 THEN PRINT "SR 1.4,2.4"
6555       PRINT "PA",X,Y,""
6560       IF Sym>3 THEN PRINT "SR 1.2,1.6"
6565       IF Sym=4 THEN PRINT "UC2,4,99,Ø,-8,-4,Ø,Ø,8,4,Ø;"
6570       IF Sym=5 THEN PRINT "UC3,Ø,99,-3,-6,-3,6,3,6,3,-6;"
6575       IF Sym=6 THEN PRINT "UCØ,5.3,99,3,-8,-6,Ø,3,8;"
6580       IF Sym=7 THEN PRINT "UCØ,-5.3,99,-3,8,6,Ø,-3,-8;"
6585    NEXT I
6590    BEEP
6595    INPUT "WANT TO LABEL (1=Y,Ø=N)?",Ilbl
6600    IF Ilbl=1 THEN
6605       IF Sym>3 THEN PRINT "SM"
6610       IF Sym<4 THEN PRINT "SR 1.4,2.4"
6615       PRINT "PA",Xal,Yal,""
6620       IF Sym>3 THEN PRINT "SR 1.2,1.6"
6625       IF Sym=4 THEN PRINT "UC2,4,99,Ø,-8,-4,Ø,Ø,8,4,Ø;"
6630       IF Sym=5 THEN PRINT "UC3,Ø,99,-3,-6,-3,6,3,6,3,-6;"
6635       IF Sym=6 THEN PRINT "UCØ,5.3,99,3,-8,-6,Ø,3,8;"
6640       IF Sym=7 THEN PRINT "UCØ,-5.3,99,-3,8,6,Ø,-3,-8;"
6645       PRINT "SM"
6650       IF Sym<4 THEN PRINT "PR 2,Ø"
6655       PRINT "PR 2,-1.Ø;SR 1.Ø,1.8;LB";D_file$;""
6660       Yal=Yal-5
6665       BEEP
6675       IF Ias=1 THEN
6680          BEEP
6685          INPUT "ENTER THE STRING",Label$
6690          PRINT "PR 2,Ø;SR 1.Ø,1.8;LB";Label$;""
6695          GOTO 6665
6700       END IF
6705    END IF
6710    BEEP
6715    INPUT "WANT TO COMBINE ANOTHER FILE? (1=Y,Ø=N)",Icomb
```

```
6720        ASSIGN @File TO *
6725        Xll=5
6730        Xul=45
6735        IF Icomb<>0 THEN 6220
6740        BEEP
6745        INPUT "WANT TO PLOT A LEAST-SQUARES LINE (1=Y,0=N)",Ils
6750        IF Ils=1 THEN
6755           BEEP
6760           INPUT "SELECT EXPONENT: 0=COMPUTE, 1=0.75)",Iexp
6765           BEEP
6770           INPUT "SELECT CURVE TYPE (0=SOLID,1=DASHED)",Ilt
6775           Ilt=Ilt+1
6780           PRINT "SM"
6785           IF Iexp=0 THEN
6790              Bb=(Nrun*Sxy-Sy*Sx)/(Nrun*Sx2-Sx^2)
6795           ELSE
6800              Bb=.75
6805           END IF
6810           Aa=(Sy-Bb*Sx)/Nrun
6815           Aa=EXP(Aa)
6820           PRINTER IS 1
6825           PRINT USING "10X,""a = "",Z.4DE";Aa
6830           PRINT USING "10X,""n = "",Z.4DE";Bb
6835           PRINTER IS 705
6840           In=0
6845           IF Iht=0 THEN Xxstep=Xstep/40
6850           IF Iht>0 THEN Xxstep=Xstep/10
6855           FOR Xa=Xll TO Xul STEP Xxstep
6860               IF Xa>.99*Xmax THEN 6995
6865               IF Iht=1 THEN Ya=Aa*Xa^Bb
6870               IF Iht=0 THEN Ya=Aa^(1/Bb)*(Xa*1.E+6)^((Bb-1)/Bb)
6875               IF Iht=2 THEN Ya=Aa*Xa^(Bb-1)
6880               IF Iht=0 THEN
6885                  Y=(Ya*1.E-3-Ymin)*Sfy
6890                  X=(Xa-Xmin)*Sfx
6895               END IF
6900               IF Iht=1 THEN
6905                  Y=(Ya*1.E-6-Ymin)*Sfy
6910                  X=(Xa-Xmin)*Sfx
6915               END IF
6920               IF Iht=2 THEN
6925                  Y=(Ya*1.E-3-Ymin)*Sfy
6930                  X=(Xa-Xmin)*Sfx
6935               END IF
6940               IF Y<0 THEN Y=0
6945               IF Y>100 THEN 6990
6950               IF Ilt=1 THEN
6955                  PRINT "PA",X,Y,"PD"
6960               ELSE
6965                  In=In+1
6970                  Ir=In MOD Ilt
6975                  IF Ir=1 THEN PRINT "PA",X,Y,"PD"
6980                  IF Ir=0 THEN PRINT "PA",X,Y,"PU"
6985               END IF
6990           NEXT Xa
6995           PRINT "PU"
7000        END IF
7005        Icomb=0
7010        GOTO 6185
```

```
7015    END IF
7020    PRINT "PU SM"
7025    BEEP
7030    INPUT "WANT TO PLOT NUSSELT LINE (1=Y,0=N)?",Inp
7035    IF Inp=0 THEN 7125
7040    BEEP
7045    INPUT "ENTER TSAT (DEFAULT=18 DEG C)",Tsat
7050    Hfg=FNHfg(Tsat)
7055    Xll=5
7060    Xul=45
7065    FOR Xa=Xll TO Xul STEP Xstep/50
7070        Tfilm=Tsat-Xa*.5
7075        Kf=FNK(Tfilm)
7080        Rhof=FNRho(Tfilm)
7085        Muf=FNMu(Tfilm)
7090        Ya=.728*(Kf^3*Rhof^2*9.81*Hfg/(Muf*Do*Xa))^.25
7095        X=(Xa-Xmin)*Sfx
7100        Y=(Ya*1.E-3-Ymin)*Sfy
7105        PRINT "PA",X,Y,"PD"
7110    NEXT Xa
7115    PRINT "PU PA 0,0"
7120    PRINT "PU PA 0,0 SP0"
7125    SUBEND
7130    SUB Plot3
7135    COM /Drl/ Star,Sym,Icon
7140    COM /Fid/ Ift
7145    DIM C(9)
7150    Fw=1
7155    PRINTER IS 1
7160    BEEP
7165    PRINT USING "4X,""Select Option X-Y Limits """
7170    PRINT USING "6X,""0 Use default values"""
7175    PRINT USING "6X,""1 Use new values"""
7180    INPUT Okd
7185    PRINTER IS 705
7190    IF Okd=0 THEN
7195       Xmin=0
7200       Ymin=0
7205       Xmax=15
7210       Ymax=15
7215       Xstep=3
7220       Ystep=3
7225    ELSE
7230       BEEP
7235       INPUT "ENTER MINIMUM AND MAXIMUM X-VALUES",Xmin,Xmax
7240       BEEP
7245       INPUT "ENTER MINIMUM AND MAXIMUM Y-VALUES",Ymin,Ymax
7250       BEEP
7255       INPUT "ENTER STEP SIZE FOR X-AXIS",Xstep
7260       BEEP
7265       INPUT "ENTER STEP SIZE FOR Y-AXIS",Ystep
7270    END IF
7275    BEEP
7280    PRINT "IN;SP1;IP 2300,1800,8300,6800;"
7285    PRINT "SC 0,100,0,100;TL 2,0;"
7290    Sfx=100/(Xmax-Xmin)
7295    Sfy=100/(Ymax-Ymin)
7300    BEEP
7305    Icg=0
```

```
7310    INPUT "LIKE TO BY-PASS CAGE (1=Y,0=N=DEFAULT)?",Icg
7315    IF Icg=1 THEN 7520
7320    PRINT "PU 0,0 PD"
7325    FOR Xa=Xmin TO Xmax STEP Xstep
7335        PRINT "PA",X,",0,XT"
7340    NEXT Xa
7345    PRINT "PA 100,0,PU"
7350    PRINT "PU PA 0,0 PD"
7355    FOR Ya=Ymin TO Ymax STEP Ystep
7360        Y=(Ya-Ymin)*Sfy
7365        PRINT "PA 0,",Y,",YT"
7370    NEXT Ya
7375    PRINT "PA 0,100 TL 0 0"
7380    FOR Xa=Xmin TO Xmax STEP Xstep
7385        X=(Xa-Xmin)*Sfx
7390        PRINT "PA",X,",100,XT"
7395    NEXT Xa
7400    PRINT "PA 100,100 PU PA 100,0 PD"
7405    FOR Ya=Ymin TO Ymax STEP Ystep
7410        Y=(Ya-Ymin)*Sfy
7415        PRINT "PD PA 100,",Y,",YT"
7420    NEXT Ya
7425    PRINT "PA 100,100 PU"
7430    PRINT "PA 0,-2 SP 1.5,2"
7435    FOR Xa=Xmin TO Xmax STEP Xstep
7440        X=(Xa-Xmin)*Sfx
7445        PRINT "PA",X,",0,"
7450        IF Xa<1 AND Xa<>0 THEN PRINT "CP -1.5,-1;LB0.PR -1,0;LB",Xa,""
7455        IF Xa=0 THEN PRINT "CP -.5,-1;LB0"
7460        Xin=0
7465        IF Xa MOD 1=0 THEN Xin=1
7470        IF Xa>=10 THEN PRINT "CP -2,-1;LB",Xa,""
7475        IF Xa>1 AND Xa<10 AND Xin=1 THEN PRINT "CP -1.25,-1;LB",Xa
7480        IF Xa>1 AND Xin=0 THEN PRINT "CP -2,-1;LB",Xa,""
7485        IF Xa=1 THEN PRINT "CP -1,-1;LB1.0"
7490    NEXT Xa
7495    PRINT "PU PA 0,0"
7520    Int=0       MODIFY
7525    FOR Ya=Ymin TO Ymax STEP Ystep
7510        Y=(Ya-Ymin)*Sfy
7515        PRINT "PA 0,",Y,""
7520        IF Int=0 AND Ya<0 THEN PRINT "PR 2,0"
7525        IF Ya<1 AND Ya<>0 THEN PRINT "CP -4,-.25;LB0.PR -2,0;LB",Ya,""
7530        IF Ya=0 THEN PRINT "CP -2,-.25;LB0"
7535        IF Ya>1 AND Int<2 THEN PRINT "CP -5,-.25;LB",Ya,""
7540        IF Ya>9 AND Int=2 THEN PRINT "CP -4,-.25;LB",Ya,""
7545        IF Ya>0 AND Ya<10 AND Int=2 THEN PRINT "CP -3,-.25;LB",Ya,""
7550        IF Ya=1 THEN PRINT "CP -4,-.25;LB1.0"
7555    NEXT Ya
7560    IF Ord=0 THEN
7565       Xlabel$="X"
7570       Ylabel$="Y"
7575    ELSE
7580       BEEP
7585       INPUT "ENTER X-LABEL",Xlabel$
7590       BEEP
7595       INPUT "ENTER Y-LABEL",Ylabel$
7600    END IF
7605    PRINT "SP 1.5,2 PU PA 50,-10 CP";-LEN(Xlabel$)/2,"0;LB";Xlabel$,""
```

```
7610    PRINT "PA -11,50 CP 0,"(-LEN(Ylabel$)/2*5/6,"DI 0,1,LB";Ylabel$;"
7615    PRINT "CP 0,0 DI"
7620    Nrun=0
7625    BEEP
7630    INPUT "WANT TO PLOT DATA FROM A FILE (1=Y,0=N)?",Ok
7635    Okp=0
7640    IF Ok=1 THEN
7645       BEEP
7650       INPUT "ENTER THE NAME OF THE PLOT DATA FILE",D_file$
7655       ASSIGN @File TO D_file$
7660       IF Icomb>0 THEN 7690
7665       Sx=0
7670       Sy=0
7675       Sx2=0
7680       Sxy=0
7685       Md=1
7690       BEEP
7695       INPUT "ENTER THE BEGINNING RUN NUMBER (DEF=1)",Md
7700       Npairs=9
7705       BEEP
7710       INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED (DEF=9)",Npairs
7715       BEEP
7720       INPUT "SELECT TUBE NUMBER (0=TOP,1=SECOND......)",Itube
7725       Nrun=Nrun+Npairs
7730       PRINTER IS 1
7735       BEEP
7740       PRINT USING "4X,""Select a symbol:"""
7745       PRINT USING "4X,"" 1  Star     2  Plus sign"""
7750       PRINT USING "4X,"" 3  Circle   4  Square"""
7755       PRINT USING "4X,"" 5  Rombus"""
7760       PRINT USING "4X,"" 6  Right-side-up triangle"""
7765       PRINT USING "4X,"" 7  Up-side-down triangle"""
7770       INPUT Sym
7775       PRINTER IS 705
7780       IF Sym=1 THEN PRINT "SM*"
7785       IF Sym=2 THEN PRINT "SM+"
7790       IF Sym=3 THEN PRINT "SMo"
7795       Md=Itube*9
7800       IF Md>1 THEN
7805          FOR I=0 TO (Md-1)
7810              ENTER @File;X,Y
7815          NEXT I
7820       END IF
7825       FOR I=1 TO Npairs
7830           ENTER @File;Xa,Ya
7835           Sx=Sx+Xa
7840           Sy=Sy+Ya
7845           Sx2=Sx2+Xa^2
7850           Sxy=Sxy+Xa*Ya
7855           X=(Xa-Xmin)*Sfx
7860           Y=(Ya-Ymin)*Sfy
7865           IF Y>100 OR Y<0 THEN 7910
7870           IF Sym>3 THEN PRINT "SM"
7875           IF Sym<4 THEN PRINT "SR 1.4,2.4"
7880           PRINT "PA",X,Y,""
7885           IF Sym>3 THEN PRINT "SR 1.2,1.6"
7890           IF Sym=4 THEN PRINT "UC2,4,99,0,-8,-4,0,0,8,4,0;"
7895           IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3,6,3,6,3,-6;"
7900           IF Sym=6 THEN PRINT "UC0,5.3,99,3,-8,-6,0,3,8;"
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7905         IF Sym=7 THEN PRINT "UC0,-5.3,99,-3,8,6,0,-3,-8;"
7910      NEXT I
7915      BEEP
7920      INPUT "WANT TO LABEL (1=Y,0=N)?",Ilbl
7925      IF Ilbl=1 THEN
7930         IF Sym>3 THEN PRINT "SM"
7935         IF Sym<4 THEN PRINT "SR 1.4,2.4"
7940         PRINT "PA",Xal,Yal,""
7945         IF Sym>3 THEN PRINT "SR 1.2,1.6"
7950         IF Sym=4 THEN PRINT "UC2,4,99,0,-8,-4,0,0,8,4,0;"
7955         IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3,6,3,6,3,-6;"
7960         IF Sym=6 THEN PRINT "UC0,5.3,99,3,-8,-6,0,3,8;"
7965         IF Sym=7 THEN PRINT "UC0,-5.3,99,-3,8,6,0,-3,-8;"
7970         PRINT "SM"
7975         IF Sym<4 THEN PRINT "PR 2,0"
7980         PRINT "PR 2,-1.0;SR 1.0,1.8;LB";D_file$;""
7985         Yal=Yal-5
7995         INPUT "WANT TO ADD ANOTHER STRING (1=Y,0=N)?",Ias
8000         IF Ias=1 THEN
8005            BEEP
8010            INPUT "ENTER THE STRING",Label$
8015            PRINT "PR 2,0;SR 1.0,1.8;LB";Label$;""
8020            GOTO 7990
8025         END IF
8030      END IF
8035      BEEP
8040      INPUT "WANT TO COMBINE ANOTHER FILE? (1=Y,0=N)",Icomb
8045      ASSIGN @File TO *
8050      IF Icomb<>0 THEN 7645
8055      Ils=1
8060      BEEP
8065      INPUT "WANT TO PLOT A LEAST-SQUARES LINE (1=DEF=YES,0=NO)",Ils
8070      IF Ils=1 THEN
8075         BEEP
8080         INPUT "SELECT CURVE TYPE (0=SOLID,1=DASHED)",Ilt
8085         Ilt=Ilt+1
8090         PRINT "SM"
8095         IF Iexp=0 THEN
8100            Bb=(Nrun*Sxy-Sy*Sx)/(Nrun*Sx2-Sx^2)
8105         ELSE
8110            Bb=.75
8115         END IF
8120         Aa=(Sy-Bb*Sx)/Nrun
8125         PRINTER IS 1
8130         PRINT USING "10X,""a = "",MZ.3DE";Aa
8135         PRINT USING "10X,""n = "",MZ.3DE";Bb
8140         PRINTER IS 705
8145         In=0
8150         FOR Xa=Xmin TO Xmax STEP (Xmax-Xmin)
8155            Ya=Aa+Xa*Bb
8160            Y=(Ya-Ymin)*Sfy
8165            X=(Xa-Xmin)*Sfx
8170            IF Y<0 THEN Y=0
8175            IF Y>100 THEN GOTO 8220
8180            IF Ilt=1 THEN
8185               PRINT "PA",X,Y,"PD"
8190            ELSE
8195               In=In+1
8200               Ir=In MOD Ilt
8205               IF Ir=1 THEN PRINT "PA",X,Y,"PD"
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8210                 IF Ir=0 THEN PRINT "PA",X,Y,"PU"
8215              END IF
8220           NEXT Xa
8225           PRINT "PU"
8230        END IF
8235        Icomb=0
8240        GOTO 7620
8245     END IF
8250     PRINT "PU PA 0,0"
8255     PRINT "PU PA 0,0 SP0"
8260     SUBEND
```

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